

**INSTRUMENTATION AND CALIBRATION OF X-RAY  
SCINTILLATION PAIR SPECTROMETER**

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INSTRUMENTATION AND CALIBRATION OF  
X-RAY SCINTILLATION PAIR SPECTROMETER

by

Joseph Edward Snyder, Jr.  
B.S., United States Naval Academy  
(1944)

Submitted in Partial Fulfillment of the  
Requirements for the Degree of

MASTER OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY  
(1955)

Signature of Author \_\_\_\_\_ Department of Physics, May 23, 1955

Certified by \_\_\_\_\_ Thesis Supervisor

Accepted by \_\_\_\_\_ Chairman, Departmental Committee on Graduate Students

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INVESTIGATION AND EVALUATION OF  
X-RAY CRISTALLINE PAIN SENSATION

by

James Edward Taylor, Jr.  
U.S. Naval Medical Research Laboratory  
(1955)

Submitted in partial fulfillment of the  
requirements for the degree of

MAJOR OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY  
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Signature of Author \_\_\_\_\_  
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X-RAY SCINTILLATION PAIR SPECTROMETER

by

Joseph Edward Snyder, Jr.

Submitted to the Department of Physics on May 23, 1955 in partial fulfillment of the requirements for the degree of Master of Science.

ABSTRACT

This paper describes an x-ray spectrometer designed for use at the M.I.T. linear accelerator. The spectrometer is a three-counter telescope with a thin lead radiator between the first and second counter. The first and second counters are thin plastic scintillators; the third, a thick plastic scintillator. An acceptable event is one in which there is no pulse in the first counter and a doubly ionizing pulse in the second counter in coincidence with the third counter. Such events should be electron-positron pairs originating only in the radiator. To a first approximation, the sum of the pulse heights produced in the second and third counter is proportional to the incident x-ray energy.

Thesis Supervisor: Bernard T. Feld

Title: Associate Professor of Physics

Indicated at 2001, it was an attempt to determine if the information  
contained in the document was correct and accurate.

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## I. INTRODUCTION

The intention of this paper is to describe an x-ray spectrometer designed for use at the M. I. T. linear accelerator. The spectrometer is a three-counter telescope with a thin lead radiator between the first and second counter. The first and second counters are thin plastic scintillators; the third, a thick plastic scintillator. An acceptable event is one in which there is no pulse in the first counter and a doubly ionizing pulse in the second counter in coincidence with the third counter. Such events should be electron-positron pairs originating only in the radiator. To a first approximation, the sum of the pulse heights produced in the second and third counter is proportional to the incident x-ray energy. This chapter is devoted to explaining the need for a spectrometer of this type at the linear accelerator.

Five- to 25-Mev x-rays are known to interact strongly with nuclei. Among the heavier elements, as much as 2 percent of the total absorption coefficient for 25-Mev bremsstrahlung is of nuclear rather than atomic origin. Most of the experiments have investigated the emission of heavy particles following photon absorption. Recently, however, some measurements have been made of nuclear absorption coefficients in good geometry transmission experiments<sup>1</sup> and of large-angle scattering of bremsstrahlung<sup>2</sup>.



## 1. INTRODUCTION

The invention of this paper is to describe an x-ray spectrometer designed for use at the M.I.T. Linear Accelerator. The spectrometer is a three-counter telescope with a thin lead collimator between the first and second counters. The first and second counters are thin plastic scintillators; the third, a thin plastic scintillator. An acceptable event is one in which there is no pulse in the first counter and a doubly ionizing pulse in the second counter in coincidence with the third counter. Such events should be electron-positron pairs originating only in the collimator. To a first approximation, the sum of the pulse heights produced in the second and third counter is proportional to the incident x-ray energy. This counter is devoted to recording the rate for a spectrometer of this type at the linear accelerator.

The 10-15 Mev x-rays are known to interact strongly with nuclei. From the earlier literature, as much as 5 percent of the total absorption coefficient for 10-15 Mev gamma-rays is of nuclear origin. Most of the experiments have investigated the relation of heavy nuclei to gamma-ray absorption. Recently, however, some experiments have been made of nuclear absorption coefficients in weak gamma-ray transitions. <sup>1</sup> and of their <sup>2</sup> angular distribution of gamma-rays.

The M. I. T. linear accelerator is 10 to 100 times as strong a source of 5- to 17-Mev x-rays as the usual betatron of comparable energy. This accelerator can furnish average electron currents of about 2 microamperes. It is, however, a pulsed machine with a duty ratio of only  $10^{-4}$ , and during the 1 microsecond pulse, the current reaches peaks of about 50 milliamperes. The low-duty ratio of the accelerator is a very important factor in the design of an x-ray spectrometer for use at the M.I.T. linear accelerator. The counting rate of a detector can be no more than a few counts per second, and the detector must be able to operate in the presence of a very high level of background radiation (low-energy photons and fast neutrons) present during the 1 microsecond pulse. One must use this high photon intensity of the accelerator to obtain energy resolution, good geometry, or small target size, rather than to obtain high counting rates.

A second limitation of the M. I. T. linear accelerator as a photon source imposes further restrictions on a photon detector. The electron energy spectrum of the accelerator is not only far from monochromatic, but it is difficult to keep the spectrum constant during a run and difficult to reproduce the same spectrum on subsequent runs. If one is to use all the current available and, say, thick-target bremsstrahlung in order to make as strong a photon source as possible, it is:

1. Necessary to monitor the photon spectrum itself rather than the electron current; and

The M. I. T. linear accelerator is 10 to 100 times as strong a

source of 5- to 15-Mev rays as the small detector of comparable energy. This accelerator can furnish average electron currents of about 5 microamperes. It is, however, a pulsed machine with a duty ratio of only  $10^{-4}$ , and during the 1 microsecond pulse, the current reaches a peak of about 50 milliamperes. The low-duty ratio of the accelerator is a very important factor in the design of an x-ray spectrometer for use at the M. I. T. linear accelerator. The operating rate of a detector can be no more than a few counts per second, and the detector must be able to operate in the presence of a very high level of background radiation (low-energy photons and fast neutrons) without being overloaded. One must use this high degree of selectivity of the accelerator to obtain energy resolution, good energy, or small energy size, rather than to obtain high counting rates.

A second limitation of the M. I. T. linear accelerator as a

photon source imposes further restrictions on a photon detector. The electron energy spectrum of the accelerator is not only low in energy, but it is difficult to keep the spectrum constant over a few and difficult to reproduce the same spectrum on subsequent runs. It can be seen that the current available may, say, change by 10% from run to run, and this is a serious problem in order to obtain a photon source as

possible, it is

1. Because of limited the photon spectrum itself

rather than the electron current; and



2. Very desirable to obtain as much information as possible from a single run.

The most efficient photon detector with reasonable resolution is a large volume of NaI. Such a spectrometer has been constructed by Koch<sup>3</sup>. Koch's best detector is a total absorption spectrometer with 11 percent resolution at 11 Mev, employing a NaI crystal 5 x 8 inches. His 2 x 2 x 5-inch NaI crystal gives about 20 percent resolution at 10 Mev. For use at the accelerator, the expense of such a large amount of NaI would perhaps be justified were it not for

1. The extreme sensitivity of NaI to photon radiation;
2. Its relative slow decay time of about 0.3  $\mu$  sec.

The first limitation requires the spectrometer to be enclosed in a massive amount of shielding. In a large-angle photon scattering experiment, the signal would need to be clipped to a fraction of the decay time of NaI to reduce pile-up of Compton recoil electrons. The differential cross section for Compton scattering at 90 degrees is as much as  $10^5$  times as large as cross sections one would like to measure, and the pile-up of the approximately half Mev Compton scattered photons during the 1  $\mu$  second accelerator pulse is a serious problem with any photon detector which involves pulse-height analysis.

The best energy resolution in the 5- to 17-Mev region is obtained with a magnetic pair spectrometer. Walker and McDaniel<sup>4</sup> were among the first in this field and obtained a solid angle times efficiency of approximately  $10^{-7}$  with an energy resolution (width at half





maximum) of 5.5 percent. Currently, the best energy resolution in the 5- to 17-Mev energy range is obtained by Kinsey and Bartholomew<sup>5</sup>, using a similar improved version of Walker and McDaniel's magnetic pair spectrometer. Using a 4.7 milligram/cm<sup>2</sup> gold radiator, Kinsey's best half-width is 140 kev, independent of photon energy.

The linear accelerator is a sufficiently strong source of x-rays to enable one to utilize a high-resolution, low-efficiency magnetic pair spectrometer. It should be able to measure the entire energy spectrum at one time; hence, it would have many channels and be of large size.

Another type of spectrometer, known as the three-crystal scintillation spectrometer<sup>6-8</sup>, employing three NaI 1-1/2 inch diameter crystals proves useful in the 4- to 12-Mev energy range. A typical arrangement<sup>6</sup> employs two 1-1/2 inch by 1 inch thick NaI crystals as annihilation radiation detectors and a center 1-1/2 inch by 4 inch long NaI crystal which measures the energy of the coincidence pair. Counter efficiency at 6 Mev is about  $10^{-5}$ , and width at half maximum is 7 percent.

Energy resolution with this three-crystal scintillation spectrometer at 11 Mev is 11 percent. In addition to these limitations imposed by the linear accelerator on the NaI total absorption spectrometer, the three-crystal scintillation spectrometer depends on 0.51-Mev photons in coincidence for its resolution, and hence is not easily adaptable for use at the M.I.T. linear accelerator.

maximum) of 2.5 percent. Currently, the best energy resolution in the 5- to 15-Mev energy range is obtained by Kinsey and Thompson's using a shielded ionized version of Wilson and Brinkman's magnetic field spectrometer. Using a 0.7 millimeter gold radiator, Kinsey's best half-width is 150 keV, independent of photon energy.

The linear accelerator is a sufficiently strong source of x-rays to enable one to utilize a high-resolution, low-efficiency magnetic field spectrometer. It should be able to measure the entire energy spectrum at one time; hence, it would have many channels and be of large size.

Another type of spectrometer, known as the three-crystal coincidence spectrometer, employing three 1-1/2 inch thick crystals proves useful in the 5- to 15-Mev energy range. A typical arrangement employs two 1-1/2 inch by 1 inch thick NaI crystals as anti-scatter detectors and a center 1-1/2 inch by 1 inch NaI crystal which measures the energy of the coincidence pair. Counter efficiency at 6 Mev is about 10%, and width at half maximum is 7 percent.

Energy resolution with this three-crystal coincidence spectrometer at 11 Mev is 11 percent. In addition to these limitations imposed by the linear accelerator on the full absorption spectrometer, the three-crystal coincidence spectrometer depends on 0.51-Mev photons in coincidence for its resolution, and hence is not easily adaptable for use at the 0.1-1.0 Mev linear accelerator.

A fourth approach to the problem has been attempted, which should provide:

1. Approximately 10 percent resolution at 10 Mev;
2. Small dimensions and ease of shielding;
3. Solid-angle times efficiency of about  $10^{-4}$ ;
4. Ability to measure an entire spectrum of photons from 5- to 17-Mev at a single run with several bins per resolution width;

5. Simplicity and economy as far as the actual detection is concerned. The major investment would go into the design and construction of associated electronic equipment. This same equipment would be useful for other projects at the M. I. T. accelerator (see, for example, W. J. Sawtelle, S.M. Thesis, M.I.T., May 1955).



A fourth aspect of the problem has been suggested, which

should provide:

1. Approximately 10 percent resolution at 10 days;

2. Half resolution and cost of shipping;

3. Half-time efficiency of about 10%;

4. Ability to measure an entire spectrum of phenomena

from 2-20 eV at a single run with several days per resolution

width.

5. Simplicity and economy as far as the actual data-

tion is concerned. The major investment would go into the design and

construction of associated electronic equipment. This same equipment

would be useful for other projects of the U.S. Accelerator (see,

for example, W. J. Stroh, W. K. Treadwell, W. I. T. Rep. 1957).

6. The design of the instrument should be such that it can be

used for a wide range of experiments with a minimum of

modification of the instrument.

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used for a wide range of experiments with a minimum of

## II. APPARATUS

### DESCRIPTION OF SPECTROMETER

The spectrometer scintillators are commercially available "Pilot B" crystals, density 1.03, polyvinyl toluene, para-terphenyl, para-para-prime diphenylstilbene<sup>19</sup>. Preliminary measurements indicate a decay time of less than  $3 \times 10^{-9}$  seconds<sup>20</sup>. Figure 1 shows to scale the physical arrangement of the spectrometer. The beam of photons from the source being surveyed is collimated by means of a half-inch hole in a 3-inch thick lead disk. The collimated photons are then incident on a lead foil where they interact forming pairs and Compton recoil electrons. This foil is known as the "converter." The converter is one-half inch in diameter, cemented to a thin lucite ring. The converter fits flush against scintillator No. 2, which in turn is held flush against scintillator No. 1. No. 2 scintillator is a cylinder  $3/4$  inch in diameter by  $3/16$  inch thick; No. 1 scintillator is a tapered cylinder 3 inches long, tapering from  $2-1/4$  inches in diameter to  $1-1/2$  inches in diameter one-half inch from the end. Figure 2 shows the shape and arrangement of the plastic scintillators.

Scintillator No. 1 has all its open faces wrapped in 1-mil aluminum foil to improve the light collection and to separate optically scintillator No. 1 from scintillator No. 2. The scintillation unit comprises the plastic scintillator, optical coupling, and selected RCA 5819 phototube. Figure 3 shows to scale the method of construction of unit No. 1.





Figure 1

Physical Arrangement of the Spectrometer

The axis of scintillator unit No. 3 is perpendicular to both the axis of unit No. 2 and unit No. 1.

# Figure 1

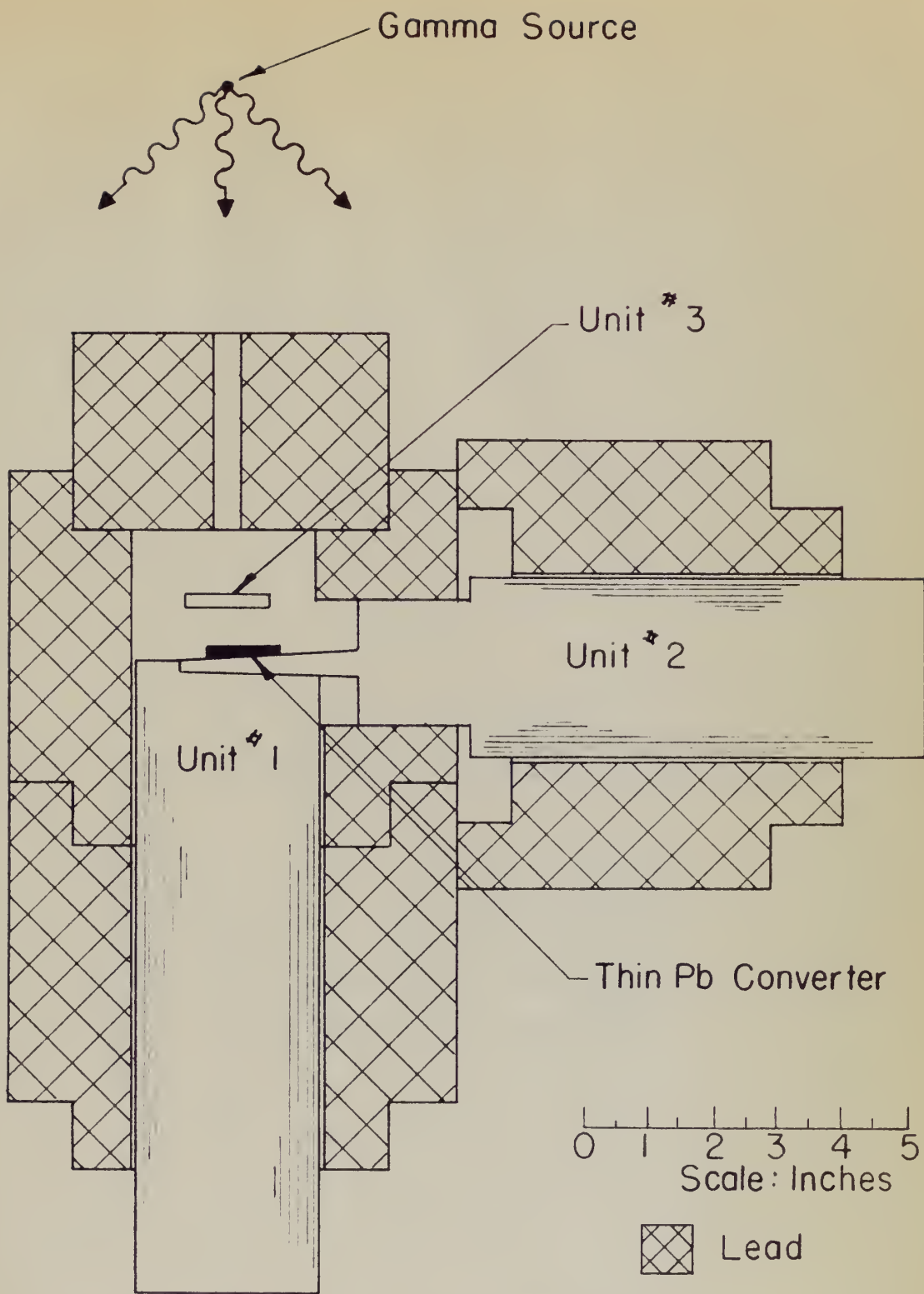
Physical properties of the specimens

The size of specimen with No. 1 is

respective to both the size of

No. 2 and with No. 1.





SHIELDING ARRANGEMENT



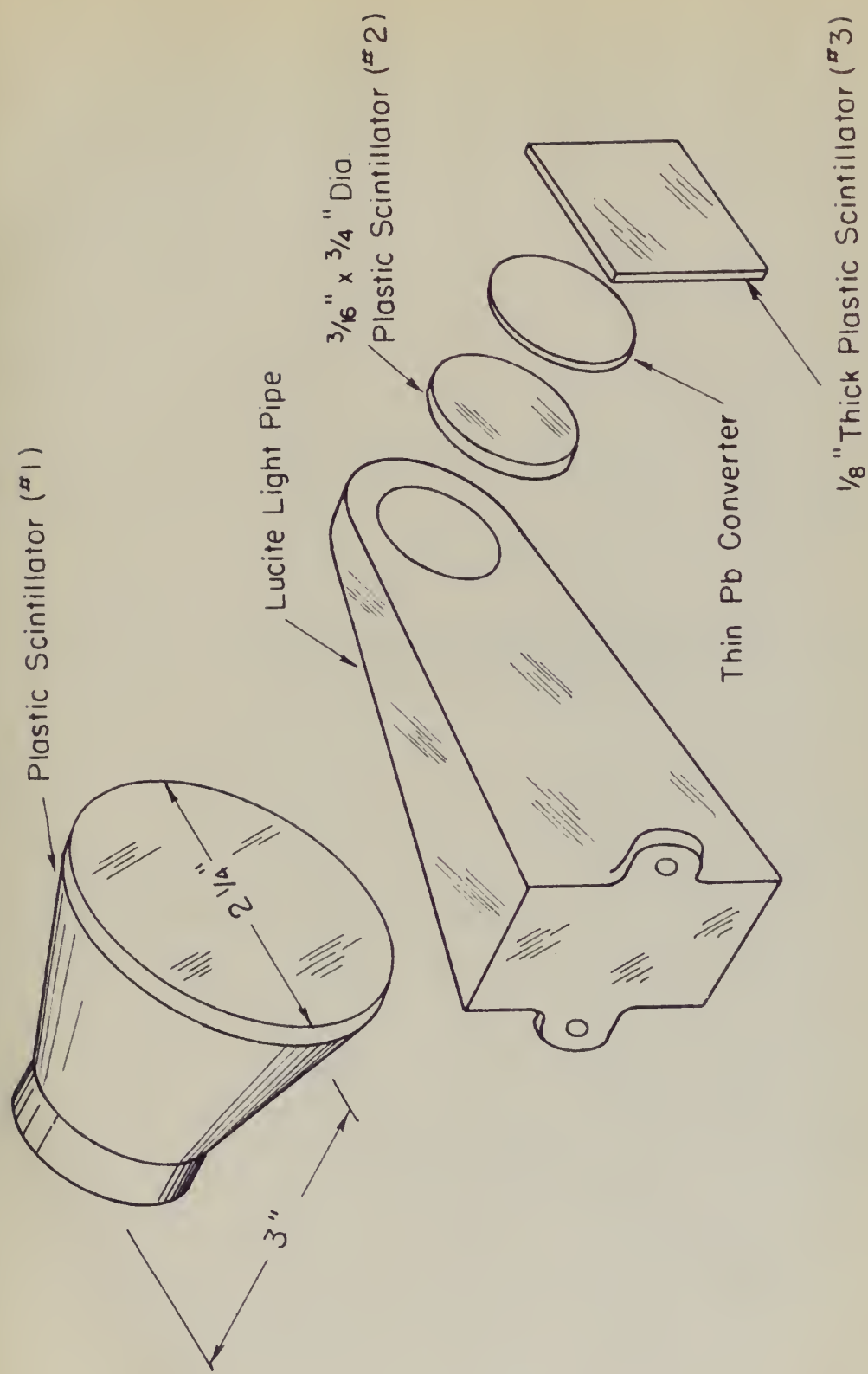
Figure 2

Arrangement and Number of the  
Plastic Reinforcers

Plastic reinforcer No. 2 is a push fit into  
the inside light pipe. The connector, No. 3  
reinforcer, and reinforcer No. 1 are held  
together by a clamp arrangement.

Figure 2  
Arrangement and Shapes of the  
Plastic Scintillators

Plastic scintillator No. 2 is a push fit into the lucite light pipe. The converter, No. 2 scintillator, and scintillator No. 1 are held together by a clamp arrangement.



ARRANGEMENT OF PLASTIC SCINTILLATORS



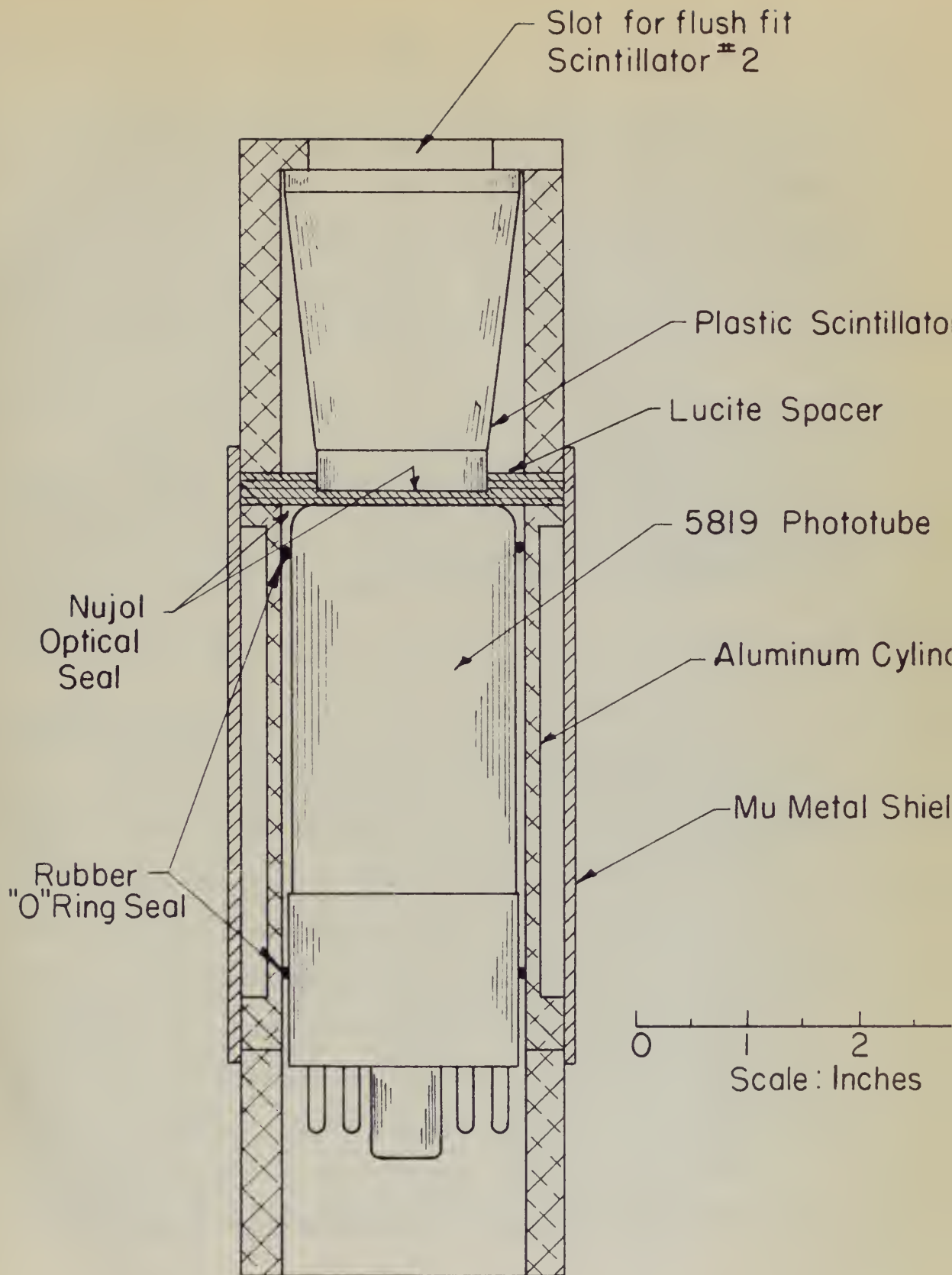
Figure 3

Construction of Scintillation Unit No. 1.

Figure 3

Comparison of behavior of the system





SCINTILLATION UNIT #1



Scintillator unit No. 2 has a 1-1/2 inch diameter, 2 inch long lucite light pipe, to which is screwed the 2-1/2 inch lucite light pipe shown in Figure 2. Scintillator No. 2 is inserted in the light pipe (push fit, Mujol optical seal). The converter holder fits into a larger diameter, 1/4 inch thick lucite ring which clamps unit No. 1 and unit No. 2 together.

Scintillator No. 3 is 1/8 inch by 1-1/8 inch, rectangular cross section, 2 inches long (shown in Figure 2). This domino-shaped plastic scintillator is held by a lucite clamp so that the standard 1-1/2 inch diameter lucite light pipe (as described for scintillator No. 2) looks at it end on.

#### ELECTRONIC CIRCUIT

The experimental equipment is shown in the block diagram of Figure 4. The gain of the system is calibrated by introducing artificial pulses (employing a Western Electric 275B relay to develop pulses of proper shape) into the input of the preamplifier. The height of these pulses is measured to an accuracy of a few tenths of a percent. The preamplifier is physically located as an integral part of the scintillation unit, bolted to the end of the aluminum housing of Figure 3. Pulses are then amplified times 30 in an amplifier whose rise time is 0.04  $\mu$  second. Unit No. 1 and unit No. 2 have two outputs. One output goes to the coincidence circuit and

Sensitizer unit No. 2 has a  $1\frac{1}{2}$  inch diameter, 2 inch long  
inside light pipe, to which is screwed the  $2\frac{1}{2}$  inch inside light  
pipe shown in Figure 2. Sensitizer No. 2 is inserted in the light  
pipe (with its optical seal). The converter holder fits into  
a larger diameter,  $1\frac{1}{2}$  inch inside light pipe which clamps unit No. 1  
and unit No. 2 together.

Sensitizer No. 3 is  $1\frac{1}{2}$  inch by  $1\frac{1}{2}$  inch, rectangular cross  
section, 2 inches long (shown in Figure 3). This dome-shaped plas-  
tic sensitizer is held by a inside clamp so that the standard  $1\frac{1}{2}$   
inch diameter inside light pipe (as described for sensitizer No. 2)  
locks at its end.

#### EXPERIMENTAL CIRCUIT

The experimental arrangement is shown in the block diagram of  
Figure 4. The basis of the system is calibrated by introducing arti-  
ficial pulses (using a Western Electric 25M relay to develop  
pulses of known shape) into the input of the photomultiplier. The  
height of these pulses is measured to an accuracy of a few tenths of  
a percent. The photomultiplier is typically located at an interval  
part of the excitation wave, placed at the end of the aluminum  
housing as shown in Figure 5. Pulses are then amplified three to an ampli-  
fier whose gain is 0.01 or more. Unit No. 1 and unit No. 2  
have two outputs. The output goes to the coincidence circuit and



the other to the addition circuit. The coincidence outputs from unit No. 1 and unit No. 2 are delay-line clipped to  $0.05 \mu$  second and delayed by  $0.03 \mu$  second to allow time for anticoincidence pulse No. 3 to function. These pulses are amplified and fed into an EFP 60-pulse shaper. The function of D2 is to discriminate against the Compton recoil electrons. D1 allows the biasing out of low-energy photons if desired. The output of EFP 60 No. 3 goes to the grid of the No. 2 Philips tube. Since the two inputs of the No. 2 EFP 60 are out of phase, if a signal exists at No. 3, there is no output from No. 2. The outputs of the No. 1 and No. 2 pulse shapers go to a diode bridge.

The measurement of the resolving time of the spectrometer was experimentally determined, using the 6-Mev fluorine gamma-ray, to be  $0.057 \mu$  second, as shown in Figure 5. A DuMont 6292 phototube was tried in unit No. 1 but proved to be unsatisfactory. The fluctuations in the transit time for the DuMont tube were so large that the cable curve was not flat on top.

The other outputs from the No. 1 and No. 2 (x 30) amplifiers are added, clipped to  $0.08 \mu$  second, stretched, and amplified as shown by the block diagram of Figure 6. The output from the diode-bridge coincidence circuit triggers a univibrator which forms a  $10 \mu$  second gate. If the gate is open, the added pulse gets through and is amplified and then is pulse height analyzed.





Figure 4

Block Diagram of Experimental Equipment

The addition and gating circuit is shown in Figure 6, the pulse-height analysis circuit in Figure 7.

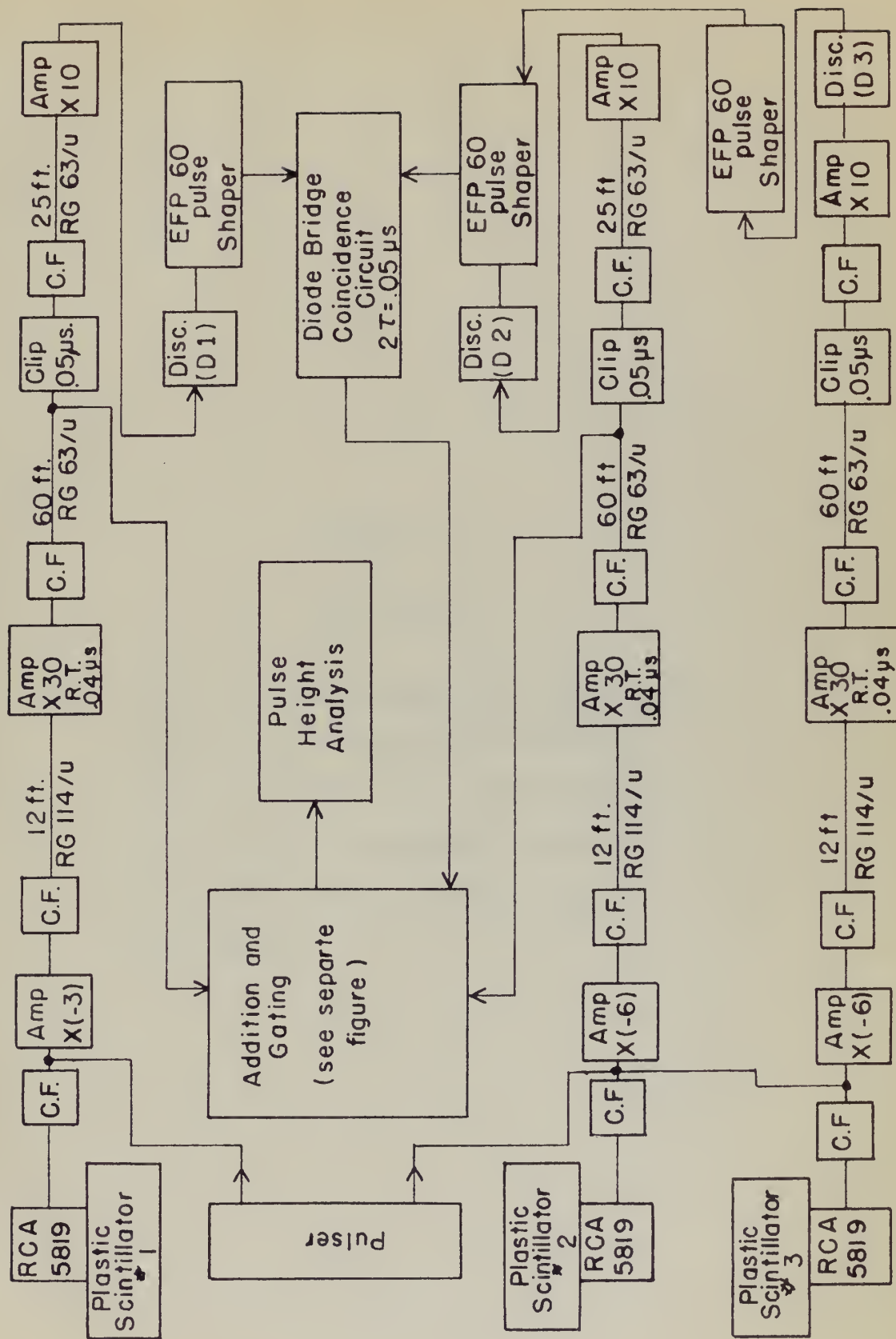
Page 2

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BLOCK DIAGRAM OF EXPERIMENTAL EQUIPMENT





Figure 5

Cable Curve

RG 63/U was used in conjunction with a  $F^{19}(p, \alpha' \gamma)$  source to determine experimentally the resolving time of the spectrometer. Each run was normalized to the same number of protons incident on the proton target.

Figure 2

Table 1

At 60 V was used in comparison with a  
 $^{10}\text{C}(\gamma, \gamma)$  source to determine experimen-  
 tally the resolving time of the spec-  
 troscopy. Both run was normalized to the  
 same number of protons incident on the  
 proton target.

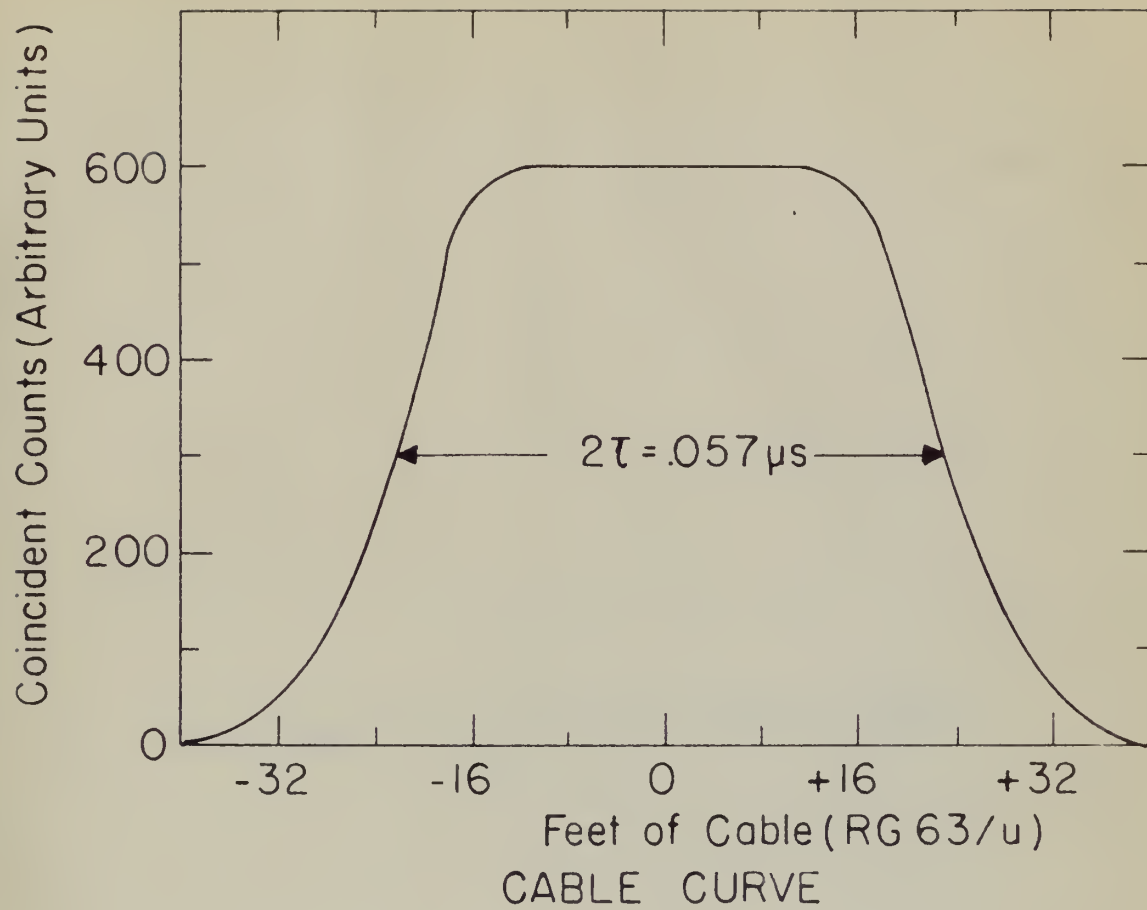




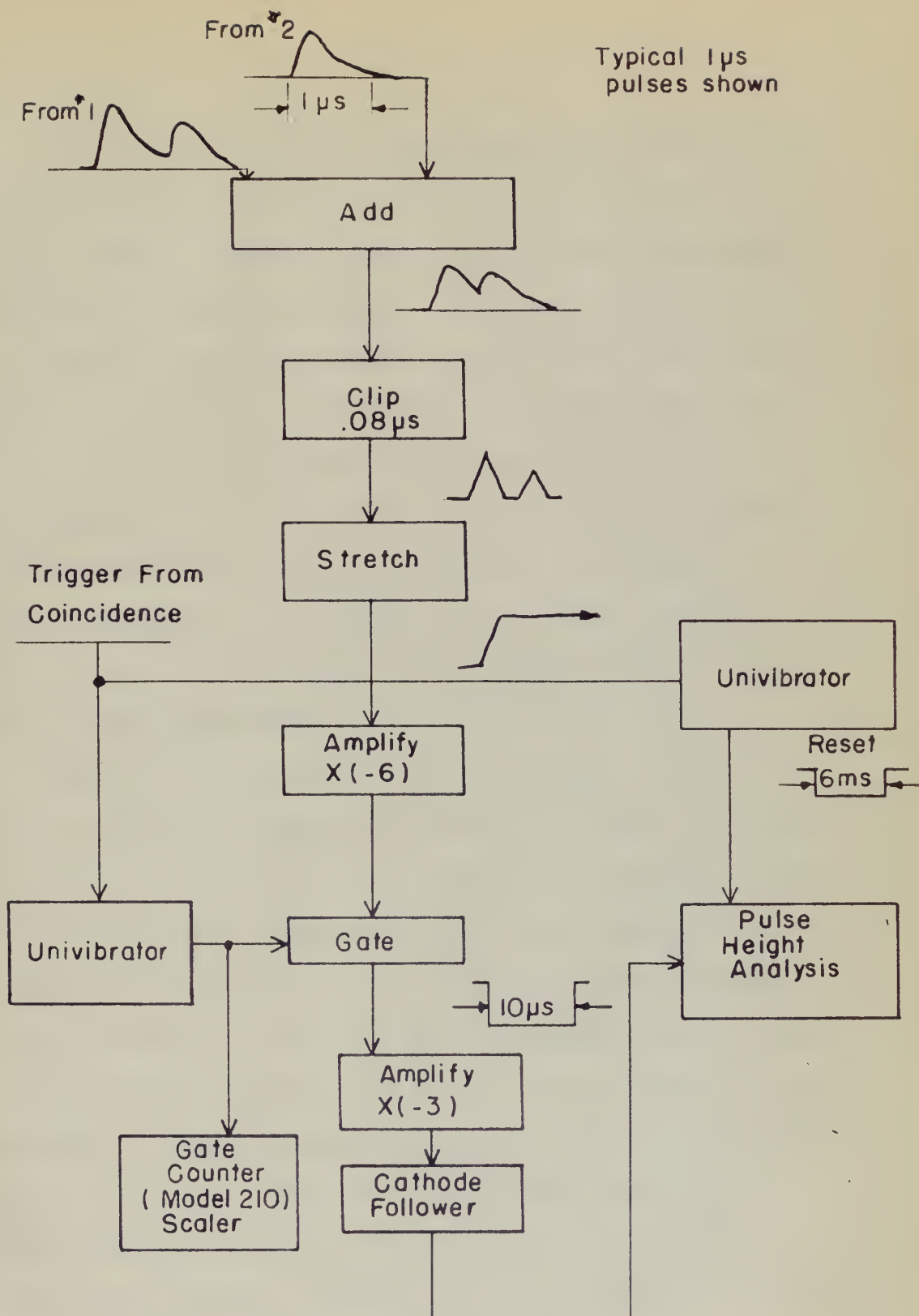
Figure 6

Block Diagram of the Addition and Gating Circuit.



Figure 6

Black squares of the addition and deletion events.



ADDITION AND GATING CIRCUIT



The pulse-height analysis circuit-block diagram is given in Figure 7. The basic principle of this pulse-height analysis is that pulse height is changed to time by a condenser discharging at constant current through a pentode. This time is accurately measured by beating a crystal-controlled oscillator on the triangular pulse and counting the oscillator pulses by a conventional binary scaler. This circuit is known as the "Multichannel Differential Discriminator," and its detailed circuit diagram may be found on file 6432, Laboratory for Nuclear Science, M. I. T., Dwg. No. D-2231-A. The output of the scaler goes to a buffer amplifier and then to one of two (or both simultaneously) methods of recording the reading of the scaler.

Figure 8 shows one method of data recording. This method provides a 128-channel recording pulse-height analyzer. Six scaler lights are in a light-tight box where they are recorded by a standard 16-mm movie camera externally driven at approximately 9 inches per minute. The framing pawl of the camera is removed to achieve continuous movement of the film. This is necessary, since the film is "framed" even though the camera shutter has been removed and made inoperative. A clock is an added feature for future identification. The film is read most easily by scanning it on a standard 16-mm microfilm reader. The pulser is turned on periodically during a run for calibration purposes. Reading time varies from 150 - 400 counts per hour, depending on energy and counting rate.

The pulse-height analysis circuit-block diagram is given in

Figure 7. The basic principle of this pulse-height analysis is that pulse height is changed to time by a condenser discharging at constant current through a period. This time is accurately measured by feeding a crystal-controlled oscillator on the triangular pulse and counting the oscillator pulses by a conventional binary scaler. This circuit is known as the "Weinmann Differential Discriminator," and the detailed circuit diagram may be found on file 612, Laboratory for Nuclear Science, M. I. T., Eng. No. D-2311-4. The output of the scaler goes to a buffer amplifier and then to one of two (or both simultaneously) methods of recording the reading of the scaler.

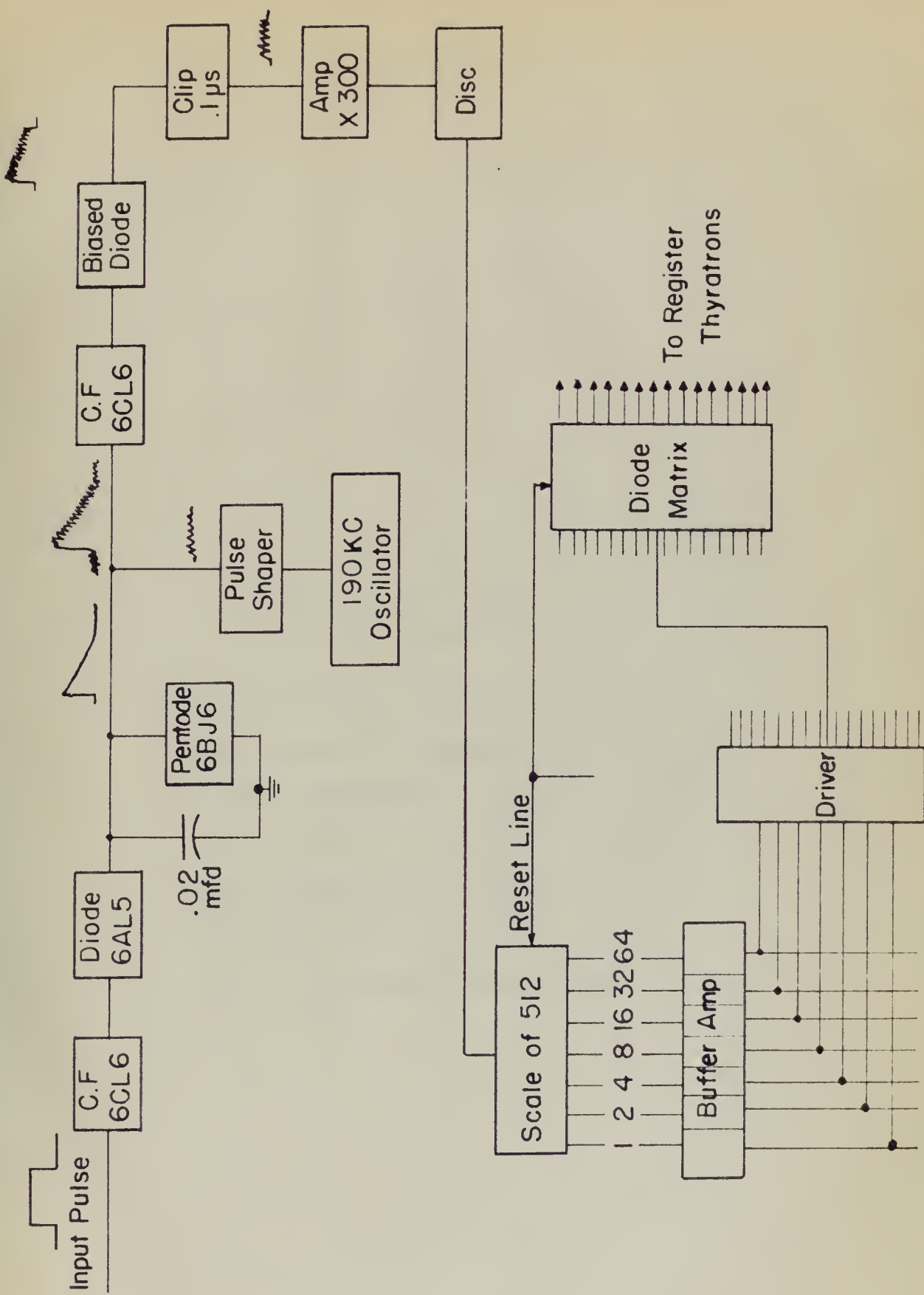
Figure 8 shows one method of data recording. This method provides a 157-channel recording pulse-height analyzer. Six scaler lights are in a light-tight box where they are recorded by a standard 16-mm movie camera externally driven at approximately 9 inches per minute. The framing panel of the camera is removed to achieve continuous movement of the film. This is necessary, since the film is "frozen" even though the camera shutter has been removed and made insensitive. A clock is an added feature for future identification. The film is read most easily by scanning it on a standard 16-mm microfilm reader. The viewer is turned on periodically during a run for calibration purposes. Reading time varies from 150 - 100 counts per hour, depending on energy and counting rate.



Figure 7

Block Diagram of the Pulse-Height Analysis Circuit





PULSE HEIGHT ANALYSIS CIRCUIT



Figure 8

Method of Recording Scaler Lights

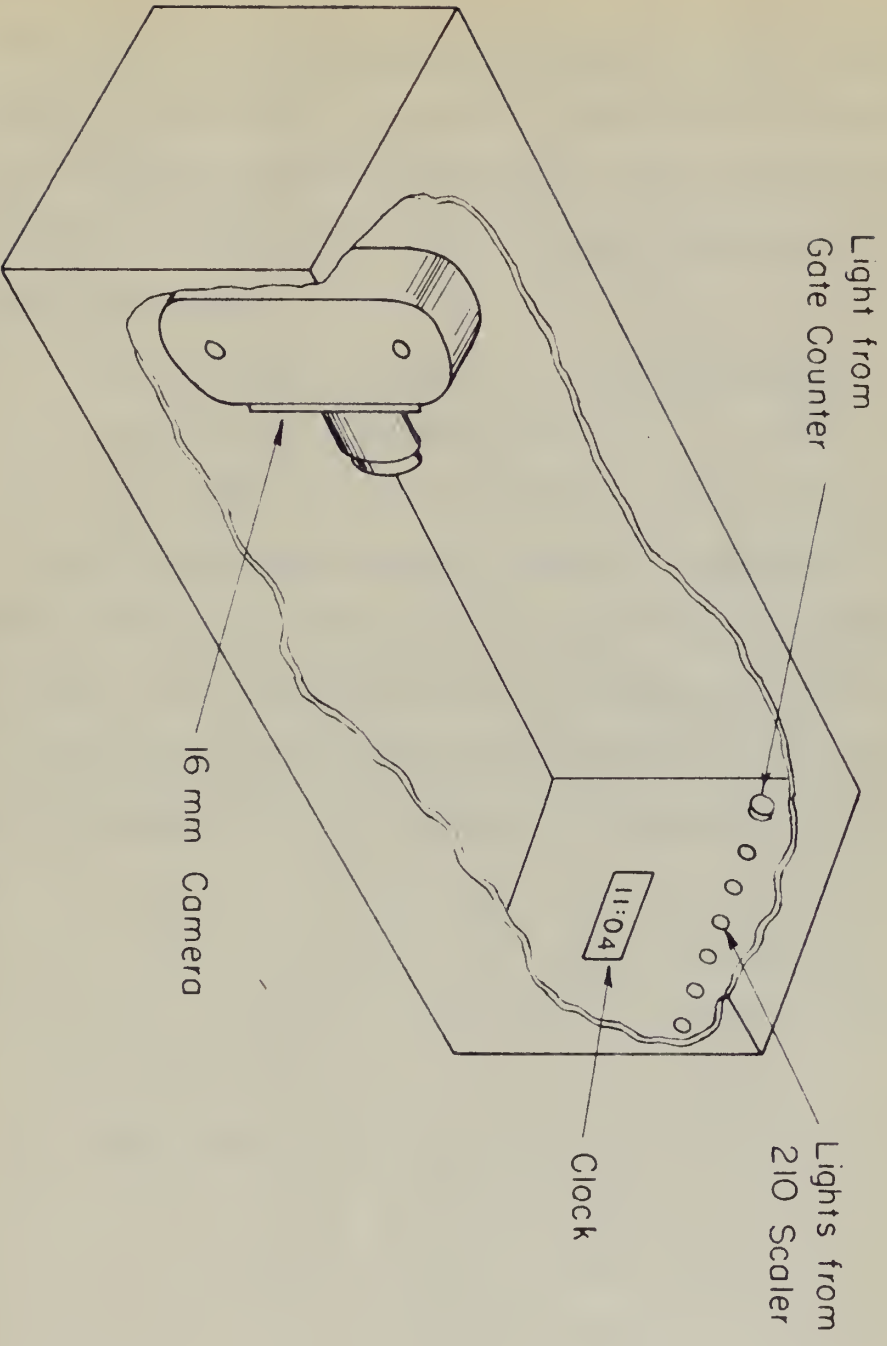
The rectangular box shown in the figure is light-tight and a standard 16-mm movie camera, equipped with a short focal length lens, records the fact that the gate was opened and the channel number. The film is externally driven at 9 inches per minute. The clock is for identification of the run.



Figure 8

Method of Recording Solar Light

The rectangular box shown in the figure is  
light-tight and a standard 16-mm movie  
camera, equipped with a short focal length  
lens, records the fact that the gate was  
opened and the channel number. The film is  
automatically driven at 9 inches per minute.  
The clock is for identification of the run.





The second method of recording the output of the analyzer is on a set of sixteen mercury registers. Essentially, the binary system of the scaler lights is converted into a scale of sixteen by means of a diode matrix. The sixteen registers can be set (by selector switch) to cover:

- a. Channels 0-15, 16-31, 32-47, ..., 112-127;
- b. Channels 0-31, 32-64, etc; or
- c. Channels 0-63 and 64-127.

Investigation of the overall electronic stability of the spectrometer has shown a drift of the order of 1 percent during a period of one hour. It has been determined that the major part of the drift originates in the addition circuit. The pulse-height analyzer itself is stable to 1 percent over a period of several hours.

The second method of recording the output of the analyzer is on a set of sixteen rotary registers. Essentially, the binary system of the scalar lights is converted into a scale of sixteen by means of a disk matrix. The sixteen registers can be set (by selector switch) to cover:

- a. Channels 0-15, 16-31, 32-47, ... , 112-127;
- b. Channels 0-31, 32-63, etc; or
- c. Channels 0-63 and 64-127.

Investigation of the overall electronic stability of the spectrometer has shown a drift of the order of 1 percent during a period of one hour. It has been determined that the major part of the drift originates in the addition circuit. The pulse-height analyzer itself is stable to 1 percent over a period of several hours.



### III. SELECTION OF PAIRS

The principle of selection of pairs created in the converter and rejection of Compton recoil electrons is accomplished by a discriminator in the output of unit No. 2 (D2 of Figure 4). Pairs are mostly emitted in the forward direction with the mean angle of bipartition given to a close approximation<sup>21</sup> by  $\theta_1 = mc^2/E_p$ , where  $mc^2 = 0.51$  Mev, and  $E_p$  = photon energy less 1.02 Mev. The collision energy loss per cm for 1- to 15-Mev electrons is constant within 10 percent if the density effect<sup>23</sup> is included. Hence, to a first approximation, a pair will lose twice as much energy in scintillator No. 2 as will a Compton recoil electron. Therefore, we require that a minimum energy loss be sustained in scintillator No. 2 in order to record a coincidence with scintillator No. 1, resulting in addition of the energy lost by collision in Nos. 1 and 2, and yielding a pulse whose height is linearly proportional to the energy of the incident photon less 1.02 Mev.

For 17-Mev incident x-rays one would expect that D2 would do a good job of separating out the pairs. Figure 9 is an estimate of the pulse-height distribution for the 17.6-Mev incident gamma. Appendix I describes the method of obtaining this figure. One need only set D2 at 1.15-Mev energy loss in order to insure adequate pair selection.

### III. SECTION ON WIND

The principle of selection of pairs created in the counter and rejection of certain results is accomplished by a discrimination in the nature of the pairs (S or T pairs).

Results are obtained in the counter direction with the same kind of

discrimination given as a good approximation  $\frac{1}{2} \mu_0 = m_0^2 \sqrt{2}$ , where

$m_0^2 = 0.21$  MeV, and  $\frac{1}{2} \mu_0 =$  photon energy has 1.02 MeV. The coll-

imation energy has for the 1- to 11-MeV electrons in comparison with

in 10 percent of the energy effect is indicated. Thus, in a first

approximation, a pair will have about as much energy as the electron

has. This will be a function of the electron. Therefore, we require that

a minimum energy level be maintained in selection. This is achieved by

using a discriminator with sensitivity No. 1, resulting in a selection

of the energy lost by collision in Nos. 1 and 2, and yielding a

value which is directly proportional to the energy of the

incident electron from 1.02 MeV.

The 11-MeV incident energy was not used because that DS would be

a good job of separating out the noise. Figure 9 is an estimate of

the noise level in the 11-MeV incident energy. About

the I described the method of obtaining this figure. The need only

set up at 11-MeV energy level in order to know about the pair selec-

tion.

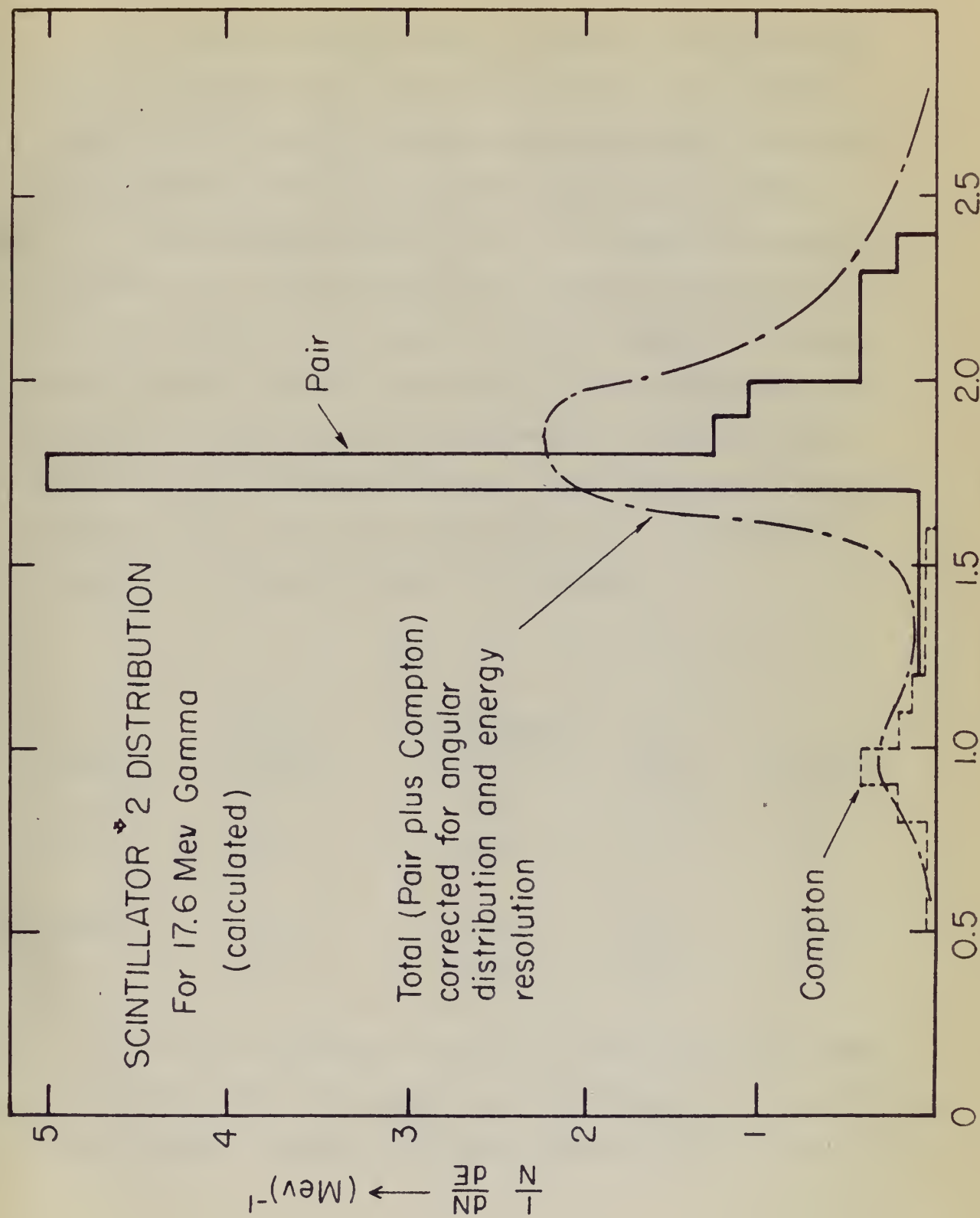
Figure 9

Calculated Differential Energy Distribution Curves  
for Scintillator No. 2, 17.6 Mev, 16-mil Pb Converter

The method of calculation of the curves is explained in Appendix I. The contribution to the distribution by pairs and Compton recoil electrons formed in the scintillator itself has not been taken into account.











At 6 Mev, a worthwhile estimate of the pulse-height distribution for scintillator No. 2 could only be obtained by a detailed "Monte Carlo"<sup>14</sup> calculation, which has not been carried out. It is more difficult to separate the pairs at 6 Mev than at 17 Mev.

Pairs and Compton recoil electrons may originate in scintillators themselves. If these electrons originate in scintillator No. 1, a coincidence will not be recorded. If they originate in the anti-coincidence unit, they will lose enough energy to trigger the anti-coincidence circuit and a coincidence count will not be recorded. However, if these electrons originate in scintillator No. 2, the possibility exists of recording a coincidence count. For comparison purposes, we examine the relative probabilities:

TABLE I

<u>Process</u>	<u>16-mil Lead Converter</u>	<u>Scintillator No. 2</u>	<u><math>E_{\gamma}</math></u>	<u>Reference</u>
Compton	0.7	0.9	6	25
Pair	1.0	0.1	6	44
Compton	0.32	0.39	17	25,29
Pair	2.1	0.25	17	29

Any pairs originating in unit No. 2, which lose enough energy in scintillator No. 2 to trigger D2, will contribute to a sharp resolution function. However, any Compton recoil electrons which are

at 6 Hz, a systematic estimate of the pulse-height distribution for installation No. 2 could only be obtained by a detailed "Monte Carlo" calculation, which has not been carried out. It is more difficult to separate the pulse at 6 Hz from at 17 Hz. Tests and constant pulse-height estimates in installation No. 1, show that, if these estimates are obtained in installation No. 2, a comparison will not be possible. If they are obtained in the anti-coincidence unit, they will have enough energy to trigger the anti-coincidence circuit and a coincidence count will not be recorded. However, if these estimates are obtained in installation No. 2, the possibility exists of recording a coincidence count. For comparison purposes, we assume the relative probabilities:

TABLE I

Relative	$\frac{P}{Y}$	Installation No. 2	16-MHz Pulse-Height	Remarks
22	6	0.9	0.7	Constant
14	6	0.1	1.3	Anti
22, 23	17	0.29	0.32	Constant
23	17	0.22	2.1	Anti

The pulse recorded in unit No. 2, which has enough energy in installation No. 2 to trigger No. 2, will contribute to a sharp peak in the spectrum. However, any constant pulse-height estimates will give

multiply scattered in scintillator No. 2 so as to trigger unit No. 2 (increased path length, increased energy loss by ionization) will result in the broadening of the shape of the spectrum, particularly on the low-energy side, because of the continuous Compton distribution. Qualitatively, it is seen that only low-energy Compton recoil electrons have a large probability of multiple scattering which, combined with their larger angle of emission (Appendix I), make this group the most troublesome. Hence, one way of cutting down the low-energy tail resulting from the Compton effect is to raise the bias of D1 or reduce the thickness of scintillator No. 2.

initially contained in amplifier No. 2 so as to return with No. 2 (instead with lamp) increased energy from by feedback will result in the widening of the range of the spectrum, particularly on the low-energy side, because of the continuous down on distribution. Qualitatively, it is seen that only low-energy down would electrons have a large probability of certain scattering which combined with their larger range of action (Appendix 1), with this group the most noticeable. Hence, one way of cutting down the low-energy tail resulting from the constant effect is to raise the bias of 11 or reduce the thickness of amplifier No. 2.

It is noted that the spectrum of amplifier No. 2 is very similar to that of amplifier No. 1, but the low-energy tail is much more pronounced.

Table 1

Amplifier	Gain	Resolution	Low-energy tail
No. 1	10	100	Small
No. 2	10	100	Large
No. 3	10	100	Small
No. 4	10	100	Small
No. 5	10	100	Small
No. 6	10	100	Small

The results of the measurements show that the low-energy tail is much more pronounced in amplifier No. 2 than in the other amplifiers. This is due to the fact that the gain of amplifier No. 2 is much higher than that of the other amplifiers.



#### IV. FUNCTION OF SCINTILLATOR NO. 3.

Up to this point, it has been unnecessary to discuss scintillator No. 3 as the operation of the spectrometer as designed only requires unit No. 1 and unit No. 2, as previously described. At the near surface of scintillator No. 2, there may exist a high-level electron background. Most of these electrons come from the collimator.

For a 17-Mev incident gamma-ray, this large number of scattered electrons is an order of magnitude larger than the number created purposely in the converter. Some of these electrons will lose a sufficient amount of energy in scintillator No. 2 to contribute to the coincidence counting rate.

One can get rid of these electrons either by a magnet or by a third scintillator in anticoincidence. The setting of the discriminator on unit No. 3 is not critical. D3 is set so that a minimum ionizing particle in passing straight through scintillator No. 3 causes the anticoincidence circuit to operate.

IV. POSITION OF ANTENNAE NO. 2.

On this subject, it has been necessary to discuss antenna No. 2 in the position of the structure as desired only in relation with No. 1 and with No. 3, as previously described. As the only a series of illustrations No. 2, shows my view of a high-level antenna structure. Just as these antenna come from the millimeter. For a 17-inch antenna structure, this large number of meters placed antenna in an order of magnitude larger than the number placed normally in the structure. Some of these antenna will have a sufficient amount of energy in antenna No. 2 to contribute to the antenna coupling rate.

One end of the antenna with a support or by a third antenna in antineutrality. The setting of the antenna on with No. 3 is not explicit. It is not as that a minimum focusing results in having antenna through antenna No. 2 across the antineutrality circuit to operate.

## V. RESOLUTION

Ideally, a monochromatic 5- to 17-Mev x-ray will interact with the converter forming pairs and Compton recoil electrons. As previously discussed, scintillation unit No. 2 will discriminate against the Compton recoil electrons, and pairs only will be recorded as coincidence counts, resulting in a single pulse height corresponding to  $E_\gamma - 1.02$ , where  $E_\gamma$  is incident monoenergetic x-ray energy in Mev. Resolution is defined as the width in Mev at half maximum divided by the peak energy in Mev.

The resolution of this spectrometer is determined by the following factors:

1. Light collection and photomultiplier statistics;
2. Radiation energy loss in the scintillators;
3. Electron escape from the scintillators;
4. Energy loss in the converter;
5. Capture of one or both annihilation quanta.

### LIGHT COLLECTION AND PHOTOMULTIPLIER STATISTICS

The absorption of light is small<sup>17</sup> in plastic scintillators, such as "Pilot B." Photomultiplier statistics can be treated in good approximation<sup>10,31,32</sup> as a statistical fluctuation in the number of photoelectrons at the first dynode of the photomultiplier.



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divided by the peak energy in Mev.

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1. Direction of wave or both oscillation periods.
2. Energy loss in the compound.
3. Direction waves from the oscillators.
4. Radiation energy loss in the oscillators.
5. Light oscillation and photomultiplier statistics.

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per of absorption of the first group of the monomers.

Good agreement <sup>10,11,12</sup> as a statistical treatment in the case  
such as "first 2." The statistical treatment can be treated in  
the absorption of light in small <sup>13</sup> in glass solubility.

Mark and Goldring<sup>13</sup> have measured the resolution of the Cs<sup>137</sup> 624-kev internal conversion line, using "Pilot B" scintillator and have obtained a value of 15 percent, as compared with 7 percent for NaI. This result implies an average of about 60 photoelectrons per Mev energy loss in the scintillator.

Using this figure of 60 photoelectrons per Mev energy loss and assuming that the light collection efficiency for scintillator No. 2 is half that for scintillator No. 1, we arrive at the following contributions to the energy resolution of the spectrometer resulting from light collection and photomultiplier statistics:

$E_{\gamma}$	Resolution (Percent.)
6	14
10	10
17	7

#### RADIATION ENERGY LOSS

Electron energy loss by radiation does not contribute to scintillator fluorescence. Bethe and Heitler<sup>14</sup> give the probability,  $P_{\alpha}$ , that an electron traversing  $t$  radiation lengths will have an energy loss less than  $\alpha$  times its initial energy (neglecting loss by ionization) as:

$$P_{\alpha} = \frac{\alpha^{t/\log 2}}{(t/\log 2)!},$$



Mark and Goldring<sup>12</sup> have measured the resolution of the Cs<sup>137</sup>

63-keV internal conversion line, using "Pilot B" scintillator and have obtained a value of 12 percent, as compared with 7 percent for NaI. This result implies an average of about 60 photoelectrons per keV energy loss in the scintillator.

Using this figure of 60 photoelectrons per keV energy loss and assuming that the light collection efficiency for scintillator No. 2 is half that for scintillator No. 1, we arrive at the following contribution to the energy resolution of the spectrometer resulting from light collection and photomultiplier statistics:

Resolution (Percent.)	$\frac{E}{Y}$
11	2
10	10
7	17

#### SCINTILLATOR ENERGY LOSS

Electron energy loss by radiation does not contribute to scintillation fluorescence. With and without<sup>13</sup> this loss the probability,  $P$ , that an electron traversing a radiation length will have an energy less than  $x$  times the initial energy (neglecting loss by ionization) is:

$$P = \frac{\sqrt{2x}}{1 + \sqrt{2x}}$$

where  $t$  is the thickness in radiation lengths<sup>27</sup>. A plot of this function for a 10-Mev electron traversing its total range is shown in Figure 10. If ionisation losses and variation of the radiative loss with energy are taken into account<sup>35</sup>, the effect will be to decrease further the low-energy tail. Examination of the energy distribution of the pairs<sup>9,15</sup> reveals that the low-energy tail will be further decreased; and, consequently, radiative loss at 17-Mev incident x-ray energy will not appreciably affect the resolution. Pairs from a 6-Mev incident x-ray will have negligible loss by radiation.

#### ELECTRON ESCAPE

Some of the electrons and positrons may escape from the scintillator. In calculating electron escape probability, the electron or positron was assumed to enter scintillator No. 2 at an average angle  $\theta_0$  (see Appendix I). The gaussian approximation of Rossi and Greisen<sup>27</sup> for the lateral displacement was graphically integrated taking into account the energy loss by collision. The mean square angle of scattering in the gaussian approximation<sup>27</sup> is:

$$\frac{E_s^2 t}{2 p^2 \beta^2},$$

where the meaning of the symbols is given in Appendix I. Thus, we find that a 15-Mev electron has an 18 percent probability of escaping with more than 1.5 Mev. Weighting the escape probability with

where  $\theta$  is the distance in radians between the two points of view. The function for a 10-ray electron traversing the total range is shown in Figure 10. In calculating losses and variation of the electron loss with energy the value  $\theta = 180^\circ$  was used, the error will be 10 percent. Figure 10 is the energy loss. The variation of the energy distribution of the ions  $H^+$  remains the same as the ion energy will be reduced by 10 percent, and, conversely, the electron loss will be 10 percent more. The energy will not necessarily follow the variation. With a 10-ray electron beam will have negligible loss by ionization.

# Electron Beam

One of the electrons and positrons may escape from the electron. In calculating electron escape probability, the electron at position was assumed to enter uniformly at  $x = 0$  at an energy  $E_0$  (see Appendix I). The electron spectrum of ions and positrons for the lateral dimension was previously integrated. Figure 10 shows the energy loss by collision. The mean square angle of scattering in the electron spectrum is given by the equation:

$$\frac{d\theta^2}{dx} = \frac{4\pi e^4}{m^2 c^2} \frac{1}{v^2} \frac{1}{v^2} \frac{1}{v^2}$$

where the number of the electrons is given in Appendix I. Thus, the total angle of the electron beam is 1.5 degrees. The electron beam with mean angle 1.5 degrees. The electron beam with mean angle 1.5 degrees.

Figure 10

Electron Energy Loss by Radiation

This curve is the differential probability of energy loss by radiation for 100 10-Mev electrons traversing 0.15 radiation lengths in carbon.



The first of these is the fact that the rate of energy loss by radiation is proportional to the square of the velocity of the particle. This is in contrast to the case of energy loss by ionization, which is proportional to the velocity. The second is that the rate of energy loss by radiation is proportional to the mass of the particle. This is also in contrast to the case of energy loss by ionization, which is independent of the mass. The third is that the rate of energy loss by radiation is proportional to the square of the charge of the particle. This is also in contrast to the case of energy loss by ionization, which is independent of the charge.

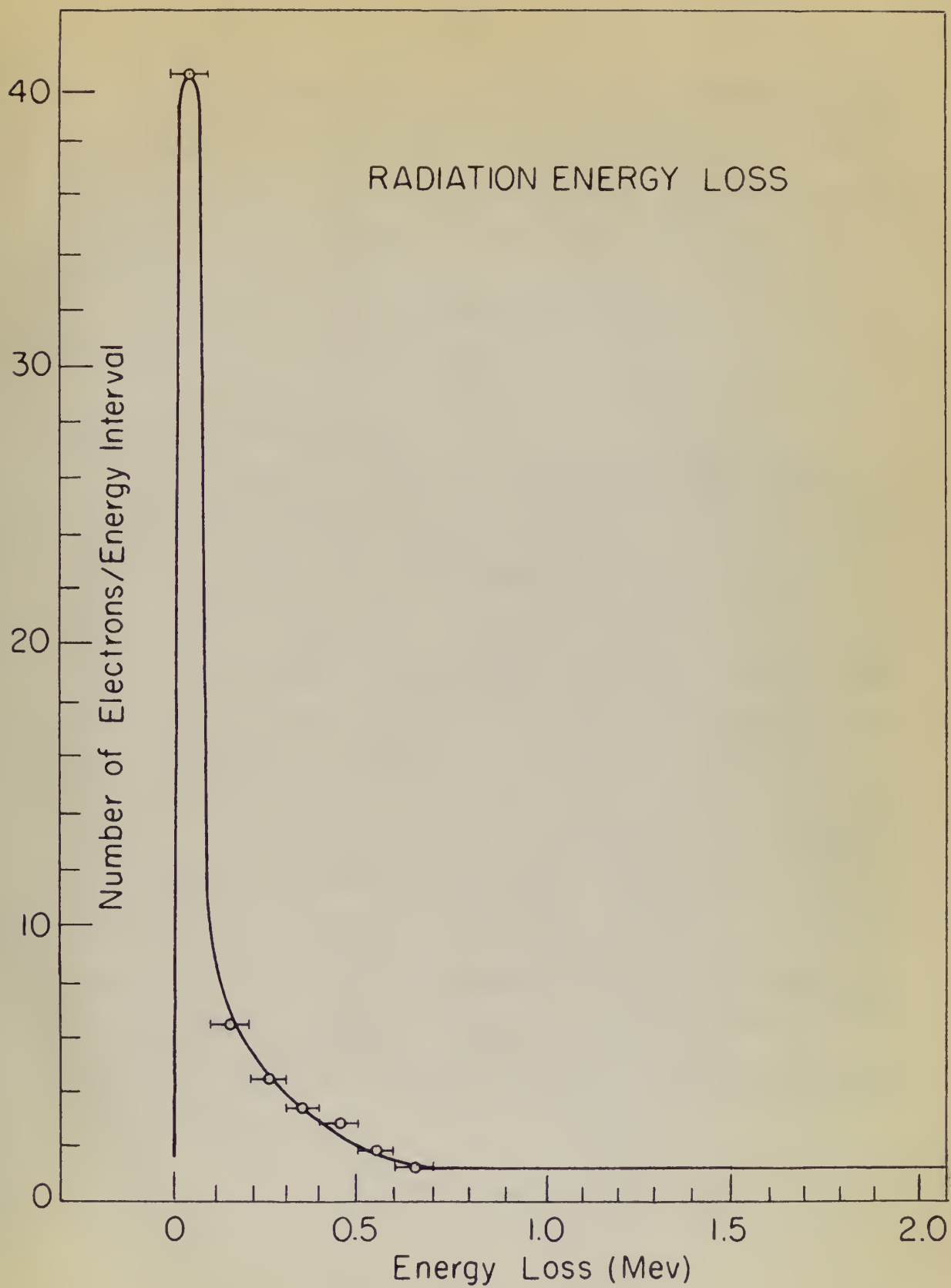
### Figure 10

#### Electron Energy Loss by Radiation

This curve is the differential probability of energy loss by radiation for 100 keV electrons traversing 0.15 radiation lengths in carbon.

The curve shows a sharp peak at a small energy loss, which is characteristic of the bremsstrahlung process. The energy loss is measured in units of the initial energy of the electron. The curve is plotted on a logarithmic scale, showing the relative probability of energy loss as a function of the energy loss itself. The peak of the curve is at approximately 0.01 of the initial energy, which corresponds to a radiation length of about 0.15. The curve then falls off rapidly as the energy loss increases further.







the pair energy distribution function<sup>24</sup> gives the approximate resolution caused by electron escape. This is negligible for a 5-Mev x-ray, of the order of 6 percent for the 17-Mev incident x-ray, and a rapidly increasing function of energy above 15-Mev x-ray energy. The length of scintillator No. 1 is equal to the range<sup>36</sup> of a 16-Mev electron.

#### ENERGY LOSS IN THE CONVERTER

The electron pair created in the converter loses energy in the converter and in the aluminum foil before entering the scintillator. This energy loss is not a constant, and the fluctuations in this energy loss contribute to the energy resolution of the spectrometer. The fluctuation of energy loss occurring when electrons pass through absorbers that are thin compared with their range has been experimentally measured<sup>37-39</sup> and found to agree with the Landau theory<sup>40</sup>. The net effect of multiple scattering is to increase the relative number of low-energy electrons<sup>28</sup>. The rms fluctuation in energy loss can be most easily calculated using Yang's  $\Delta$  correction and assuming the gaussian distribution for the multiple scattering (see Appendix I). Proceeding along these lines, we calculate a root mean square energy loss, which, when divided by the electron energy, gives resolution.

The only energy distribution function  $S_1$  gives the approximate ratio of the number of electrons having a given energy to the total number of electrons. This is negligible for a 2-MeV beam, of the order of 6 percent for the 17-MeV beam, and a rapidly increasing function of energy above 15-MeV energy. The length of the distribution  $S_1$  is equal to the range  $R$  of a 10-MeV electron.

### ENERGY LOSS IN THE CONVERTER

The electron path created in the converter loses energy in the converter and in the electron path before entering the scintillator. This energy loss is not a constant, and the fluctuations in this energy loss contribute to the energy resolution of the spectrometer. The fluctuations of energy loss contribute when electrons pass through elements that are also covered with their range has been experimentally measured  $^{17-20}$  and found to agree with the range theory  $^{10}$ . The net effect of multiple scattering is to increase the relative error of low-energy electrons  $^{21}$ . The net fluctuation in energy loss can be more easily calculated when there is a correction and assuming the Gaussian distribution for the multiple scattering (see Appendix I). Proceeding along these lines, we calculate a root mean square energy loss, which, when divided by the electron energy, gives resolution.



The aluminum foil used to wrap the scintillator has a total thickness of 3 mils. At 6 Mev, the energy loss calculated as outlined above is of the order of 1 percent; at 17 Mev, this loss is negligible.

The converter can be approximated as an electron point source covered with a foil of half converter thickness. The angular distribution of the electrons in pair production will in general have the same effect as multiple scattering; that is, electrons will not travel a constant straight-line path through the foil but will be distributed in direction (hence, path length) according to the pair production angular distribution. Since a characteristic angle of emission (see Appendix I) is inversely proportional to energy, as also is the root mean square angle of scattering, the ratio of these two angles is roughly independent of energy for a given converter thickness. No gain in resolution can be achieved by reducing the converter thickness beyond the point where the root mean square scattering angle becomes equal to the average angle of pair emission.

Assuming an average electron energy equal to one-half ( $E_\gamma - 1.02$ ), where  $E_\gamma$  is incident x-ray energy in Mev, the following results are obtained for a 16-mil lead converter:

<u><math>E_\gamma</math></u>	<u>Resolution (Percent.)</u>
6	14
11	5.7
17	3.5



The aluminum foil used to wrap the metalization has a total thickness of 3 mils. At 6 W, the average loss contained in one inch more is of the order of 1 percent; at 12 W, this loss is negligible.

The converter can be characterized as an electron beam source covered with a foil of half centimeter thickness. The angular distribution of the electrons in this position will be assumed to have the same effect as multiple scattering; that is, electrons will not travel a constant straight-line path through the foil but will be distributed in direction (angle, path length) according to the scattering angular distribution. Since a characteristic angle of electron (see Appendix I) is inversely proportional to energy, as also is the root mean square angle of scattering, the ratio of these two angles is roughly independent of energy for a given converter thickness. No gain in resolution can be achieved by reducing the converter thickness beyond the point where the root mean square scattering angle becomes equal to the average angle of path scattering.

Assuming an average electron energy equal to 100 eV,  $(E_p = 1.02)$ , then  $E_p$  is constant energy in MeV, the following results are obtained for a 10-mil lead converter:

$\frac{E_p}{E_0}$	Resolution (Percent)
1.0	10
1.2	2.5
1.5	1.5

The effect of radiation loss in the converter is smaller than the above.

#### CAPTURE OF ANNIHILATION QUANTA

Capture of an appreciable fraction of the annihilation quanta in the scintillator will impair the energy resolution of the spectrometer.

The fraction of gamma-ray energy dissipated by a narrow beam in passing through the scintillator is not the same as the fractional loss of intensity. It is necessary to multiply the probability of each interaction process (Compton and photoelectric) by the probable fraction of the photon energy actually dissipated in the absorber as a result of the process. Using this method, one takes the value of the energy absorption coefficient to be  $0.029 \text{ cm}^2/\text{gm}$  at 0.51 Mev for "Pilot B" scintillators (Fano<sup>41</sup>).

The method used to calculate the probability that at least one annihilation quantum is absorbed is as follows: Assume an average angle of pair emission and that the range of the electron<sup>18</sup> is approximately that for aluminum. (The energy loss in mica, carbon, and air is not significantly different from that in the same weight of aluminum<sup>33</sup>.) From this stopping point, assuming the quanta are isotropically emitted back-to-back with equal energies<sup>21</sup>, we establish an average solid angle and an average path length. From this

The effect of reflection loss in the converter is smaller than

the above.

#### SYSTEM OF ANTENNA POINTS

Customs at an appropriate position of the antenna points

in the collection will result the energy radiation of the spec-

tricular.

The direction of energy is indicated by a narrow beam

in passing through the antenna is not the same as the frequency

loss of intensity. It is necessary to multiply the probability of

each individual process (constant and stochastic) by the probability

of the system energy actually directed in the direction of

a result of the process. When this method, one takes the value of

the energy radiation coefficient to be 0.009 or 0.01 for

the antenna points (Table 1).

The effect loss is calculated for probability that at least

one antenna point is situated is as follows: Assume an aver-

age angle of rays emission and that the range of the antenna is

approximately that for aluminum. (The energy loss in steel, carbon,

and air is not significantly different from that in the same weight

of aluminum.) From this starting point, assuming the points are

isotropically emitted back-to-back with equal energy, we obtain

that an average solid angle and an average path length. From this



is calculated the average energy absorbed by the scintillator, taking into account the energy distribution function of the pair electrons. At 17 Mev, about 4 percent of the annihilation quanta are absorbed in the scintillator and about 7 percent are absorbed at 6 Mev.

#### SUMMARY OF EXPECTED RESOLUTION

To summarize this chapter, assuming that the processes above are statistically independent<sup>22</sup>, one arrives at the following values for the expected resolution of the spectrometer when using a 16-mil lead converter:

<u><math>E_\gamma</math></u>	<u>Resolution</u> <u>(Percent.)</u>
6	20
10	12
17	10

is calculated the energy spread absorbed by the electron, taking into account the energy distribution function of the pair electrons. At 17 kev, about 1 percent of the annihilation events are absorbed in the scintillator and about 7 percent are absorbed at 6 kev.

# SUMMARY OF EXPERIMENTAL RESULTS

To summarize this chapter, assuming that the processes above are statistically independent, one arrives at the following values for the expected resolution of the spectrometer when using a 10-cm lead converter:

$\Delta E$	Resolution (percent)
17	10
12	12
6	20



## VI. CALIBRATION AT THE ROCKEFELLER GENERATOR

The spectrometer is calibrated by using two gamma-rays of known energies to provide the two points necessary to draw the linear characteristics<sup>9-11</sup> of the scintillator. Since there are no available monoenergetic gamma sources about 5 Mev, it is necessary to utilize gamma-rays from nuclear reactions. The source of gamma-rays generally used for this type of work is from the proton bombardment of light elements.

The source of protons for testing the spectrometer was the M.I.T. Rockefeller electrostatic generator. This generator is capable of delivering a magnetically analyzed (to within 0.1 percent) proton beam of 5 microamperes, continuously variable from 0.7 to 4 Mev. The output proton current is determined by a proton beam current integrator. The area of the proton beam at the target is about 4 square millimeters, so that for the purposes of this experiment the gamma-ray originates from a point source. Figure 11 shows a photograph of the spectrometer and proton target. A scale drawing showing distances from the source is given in Figure 1.

In view of the difficulty of preparing thin proton targets that will physically withstand high proton bombardment current, it was decided to use thick targets. Targetholders were made of 10-mil aluminum disks 2 inches in diameter. A 1/16 inch deep 1/2 inch

# VI. CALIBRATION OF THE PROTON BEAM

The spectrometer is calibrated by using two types of beam sources to provide the two points necessary to give the linear relationship<sup>6-11</sup> of the voltmeter. Since there are no suitable monochromatic beam sources about 2 MeV, it is necessary to utilize gamma-rays from radium standards. The source of gamma-rays generally used for this type of work is from the isotope of light elements. The source of the spectrometer was the U.I.T. Radioactive Isotopes Generator. This generator is capable of delivering a continuously varying (to within 0.1 per cent) proton beam of 2 MeV, continuously variable from 0.1 to 1 MeV. The output proton current is determined by a proton beam current integrator. The size of the proton beam at the target is about 1 mm in diameter, so that for the purposes of this experiment the beam was considered from a point source. Figure 1 shows a photograph of the spectrometer and proton target. A scale drawing showing distances from the source is given in Figure 1.

In view of the difficulty of measuring this proton beam that will typically extend with proton beam current, it was decided to use thick targets. Targets were made of 10-12 mil aluminum disks 1 inch in diameter. A 1/16 inch deep 1/2 inch

Figure 11

The Spectrometer in Place at the MIT Rockefeller Generator

This figure is a photograph of the spectrometer at the Rockefeller generator as it was located for testing and calibration. The proton target is shown in the right of the photograph.

The spectrum of the hydrogen atom is well known. It consists of a series of discrete lines, the wavelengths of which are given by the formula

$$\frac{1}{\lambda} = R \left( \frac{1}{n^2} - \frac{1}{m^2} \right)$$

where  $R$  is the Rydberg constant,  $n$  and  $m$  are integers, and  $\lambda$  is the wavelength. The spectrum of the hydrogen atom is shown in Figure 1.

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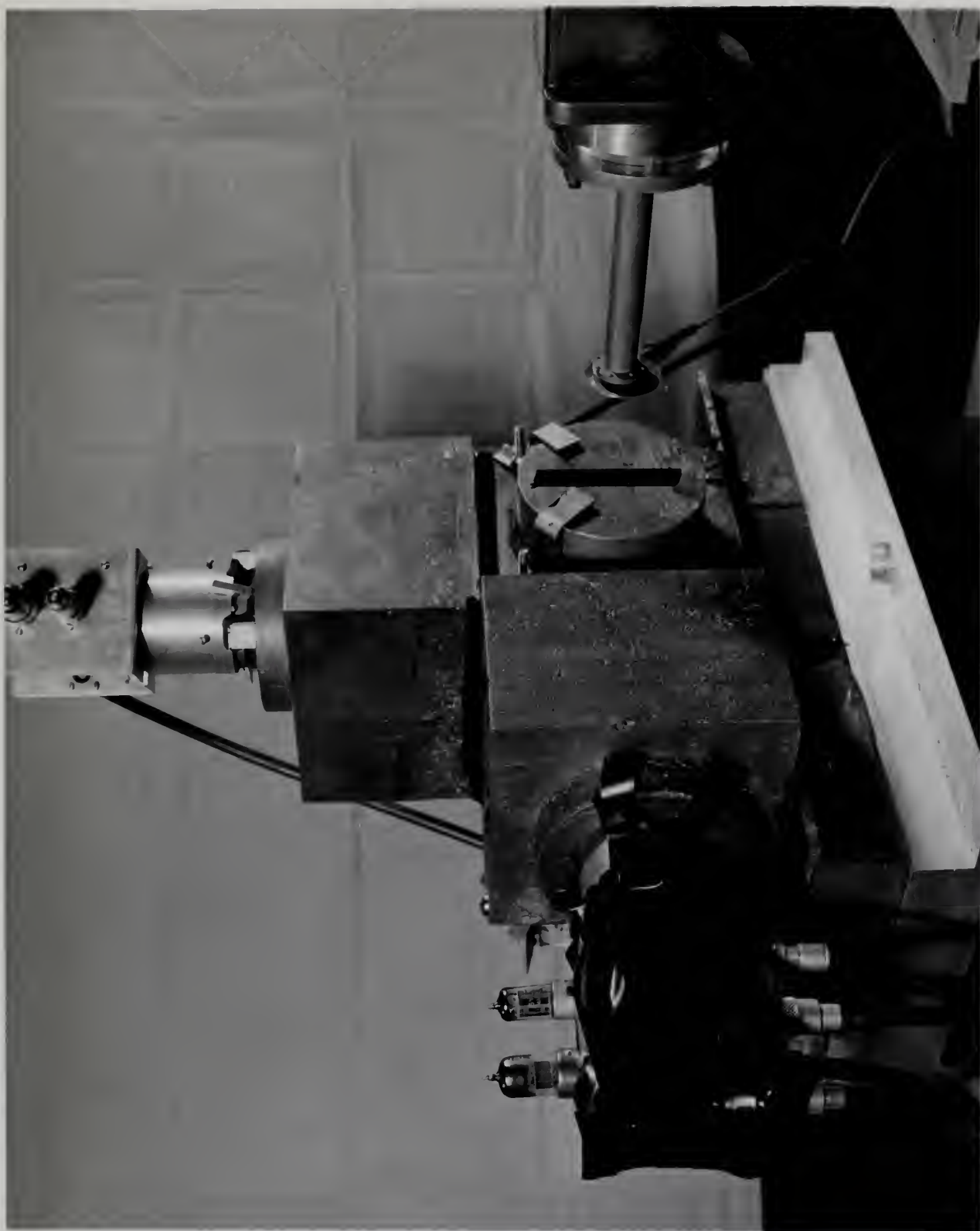
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where  $R$  is the Rydberg constant,  $n$  and  $m$  are integers, and  $\lambda$  is the wavelength. The spectrum of the hydrogen atom is shown in Figure 1.









diameter recess was formed in the center of the aluminum disk to hold the target material. Using the same die used to make the depression, the target material was pressed into the recess. This method proved satisfactory for all materials other than boron. The  $B_4C$  sample was obtained through the courtesy of Professor J. T. Norton, Metallurgical Department, M. I. T. It was in the form of a 3/16 inch thick sample, hot pressed in a graphite die.

A list of energy standards used and references giving the yields and gamma-ray energies follows:

TABLE II

<u>Target Material</u>	<u>Proton Bombardment Energy (MeV)</u>	<u>Gamma Energy (MeV)</u>	<u>Yield (<math>\gamma/10^9</math> Protons)</u>	<u>Reference</u>
$B_4C$	1.2	16.7	2	12
		12.12	4	12
		4.41	4	12
CaF	1.15	6.13	500	4,12
		7.0	200	4,12
Li Metal	1.15	17.6	20	4,16
		14.8	30	4,16

To a first approximation, the counting rate of the spectrometer is the fraction of solid angle subtended times the probability

discharge process was found in the center of the aluminum disk to hold the target material. During the run the disk was to rotate the depression, the target material was pressed into the recess. This method proved satisfactory for all materials other than boron. The  $B_{10}$  sample was obtained through the courtesy of Professor J. T. Horton, Metallurgical Department, U. I. T. It was in the form of a  $3/16$  inch thick sample, not pressed in a graphite die. A list of energy standards used and references giving the

values and gamma-ray energies follows:

TABLE II

Reference	Yield ( $\mu\text{Ci/g}$ ) ( $\mu\text{Ci/g}$ )	Gamma Energy (MeV)	Gamma Decay Constant ( $\text{hr}^{-1}$ )	Target Material
12	2	12.7	1.2	$B_{10}$
12	h	12.75		
12	h	h.11		
h, 12	200	6.13	1.12	Cd
h, 12	200	7.0		
h, 12	20	17.6	1.12	Li metal
h, 12	30	18.8		

To a first approximation, the counting rate of the spectrum over is the fraction of solid angle subtended times the probability

of producing a pair in the converter times the rate of emission of gamma radiation. The actual efficiency of the counter must be determined by experiment, since the efficiency is an unknown function of D2 and D1 settings, as well as the incident x-ray energy.

Taking into consideration target conditions, pair cross section, and solid angle which obtain at the Rockefeller generator, it was determined that the approximate times to record 1000 counts are as follows:

<u>Target</u>	<u>Time</u>
CaF	10 min
Li	1 hour
B <sub>4</sub> C	1 hour

The danger of contaminating the Rockefeller generator imposes a proton current limitation when bombarding lithium targets; this limitation is not present with B<sub>4</sub>C. This fact, coupled with the formation of LiOH at the surface, reduces the maximum attainable lithium yield by about a factor of 10, which effectively gives the same obtainable counting rate for lithium and boron.



of producing a pair in the counter from the rate of a pair of  
 from the counter. The actual efficiency of the counter must be  
 determined by experiment, since the efficiency is an important function  
 of the rate of the counter, as well as the incident x-ray energy.  
 The counter was operated under various conditions, but when the  
 rate was held constant at the rate of the counter, it  
 was determined that the efficiency was about 1000 counts per  
 as follows:

Time	Rate	Efficiency
10 min	1000	100%
1 hour	1000	100%
1 hour	1000	100%

The danger of contamination of the counter by the  
 a proton current limitation when operating the counter, this  
 limitation is not present with the counter, coupled with the for-  
 mation of the counter, reduces the counter efficiency  
 yield by about a factor of 10, which effectively gives the same ef-  
 ficiency counting rate for the counter and proton.

It was found that the counter efficiency was about 1000 counts per  
 when the rate was held constant at the rate of the counter, it  
 was determined that the efficiency was about 1000 counts per  
 as follows:



## VII. DISCUSSION OF EXPERIMENTAL RESULTS

### ENERGY CALIBRATION

The calibration of the spectrometer is in terms of the pulser voltage. The raw data are, however, recorded in terms of channel number. The channel number ( $C$ ) is related to voltage by:

$$C = f(V_{1a} + K'V_{2a}) \quad (1)$$

where  $V_{1a}$  and  $V_{2a}$  are input pulse heights in volts to the addition circuit from units Nos. 1 and 2, respectively;  $K'$  is an amplification factor determined by the parameters of the addition circuit. Assuming linearity as far as the addition circuit, equation (1) may be written:

$$C = g(V)$$

where  $V = 3(V_1 + KV_2)$ ;  $V_1$  and  $V_2$  are the output voltage of scintillation units Nos. 1 and 2, respectively.  $V$  is a pulser voltage, and the factor of 3 comes from the parameters of the circuit in which pulser and photomultiplier signals are mixed.

A typical calibration curve, giving  $C = g(V)$ , is shown in Figure 12. The calibration curve is measured both with  $V_2 = 0$  and  $V_1 = V_2$  in order to determine the addition factor  $K$ . The value of  $K$  ordinarily used was 0.450 and was stable to 0.5 percent for several hours. The nonlinearity at the upper end of the curve shown in

# VII. INTRODUCTION OF EXPERIMENTAL RESULTS

## EXPERIMENTAL CALIBRATION

The calibration of the spectrometer is in terms of the

pulsar voltage. The raw data are, however, recorded in terms of channel number. The channel number (n) is related to voltage by:

$$(1) \quad 0 = 1(V_{1a} + K_1 V_{2a})$$

where  $V_{1a}$  and  $V_{2a}$  are input pulse heights in volts to the addition circuit from units Nos. 1 and 2, respectively;  $K_1$  is an amplification factor determined by the components of the addition circuit. Assuming linearity as for an addition circuit, equation (1) may

be written:

$$0 = K(V)$$

where  $V = 3(V_1 + K_2 V_2)$ ;  $V_1$  and  $V_2$  are the output voltage of addition units Nos. 1 and 2, respectively.  $V$  is a pulsar voltage, and the factor of 3 comes from the geometry of the circuit in which

pulsar and photomultiplier signals are mixed.

A typical calibration curve, giving  $0 = K(V)$ , is shown in

Figure 12. The calibration curve is measured with  $V_2 = 0$  and

$V_1 = V$  in order to determine the addition factor  $K$ . The value of

$K$  ordinarily used was 0.450 and was stable to 0.2 percent for sev-

eral hours. The nonlinearity at the upper end of the curve shown in

Figure 12

Calibration Curve

Shown here is a typical calibration curve made before, during, and after each run.

Raw data are in the form of counts per channel as a function of channel number. Data are converted into counts per volt as a function of pulser voltage.

The following is the description of the test:

1. The test is performed in a room with a temperature of 20°C.

$$(2) \quad \frac{1}{\rho} = \frac{1}{\rho_0} + \frac{1}{\rho_1} + \frac{1}{\rho_2} + \dots$$

where  $\rho$  is the density of the mixture,  $\rho_0$  is the density of the first component,  $\rho_1$  is the density of the second component, and so on.

### Calculation of the density of the mixture

There are two methods for calculating the density of the mixture:

1. The first method is to use the formula:

2. The second method is to use the formula:

3. The third method is to use the formula:

4. The fourth method is to use the formula:

5. The fifth method is to use the formula:



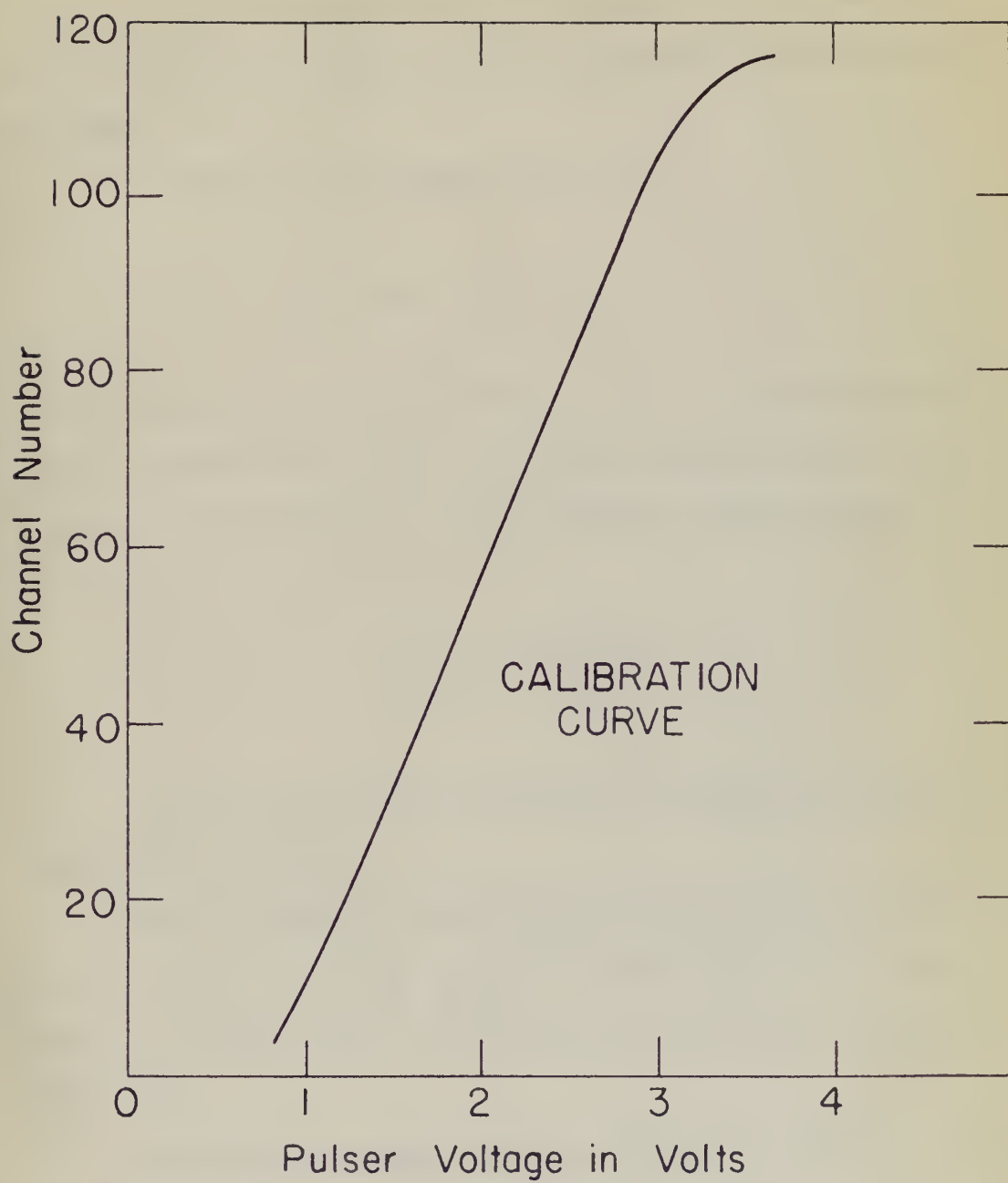






Figure 12 comes from overloading the stage of amplification just before the pulse-height analyzer. The nonlinearity in the lower part of the curve comes from diode nonlinearity in the pulse-height analyzer.

The energy of the incident x-ray is:

$$E_{\gamma} = 1.02 + E_1 + E_2 + E_0 ,$$

where  $E_1$  and  $E_2$  are energy losses (in Mev) in scintillators Nos. 1 and 2, respectively, and  $E_0$  is the most probable energy lost by electrons and positrons in the lead converter (about 0.5 Mev).

$$V = \frac{V_1}{E_1} E_1 + K \frac{V_2}{E_2} E_2 .$$

The ratios  $V_1/E_1$  may be controlled by varying the photomultiplier high voltage.

The same negative power supply furnished the high voltage for No. 1 and No. 2. This supply was stable to 0.1 percent for periods of several hours. Both photomultipliers were operated at -740 volts.

Calibration was accomplished by varying the addition factor,  $K$ , until the peaks from the 6-Mev fluorine line and the 16-Mev  $B_4C$  line fell in the correct relative positions (see Figure 13).



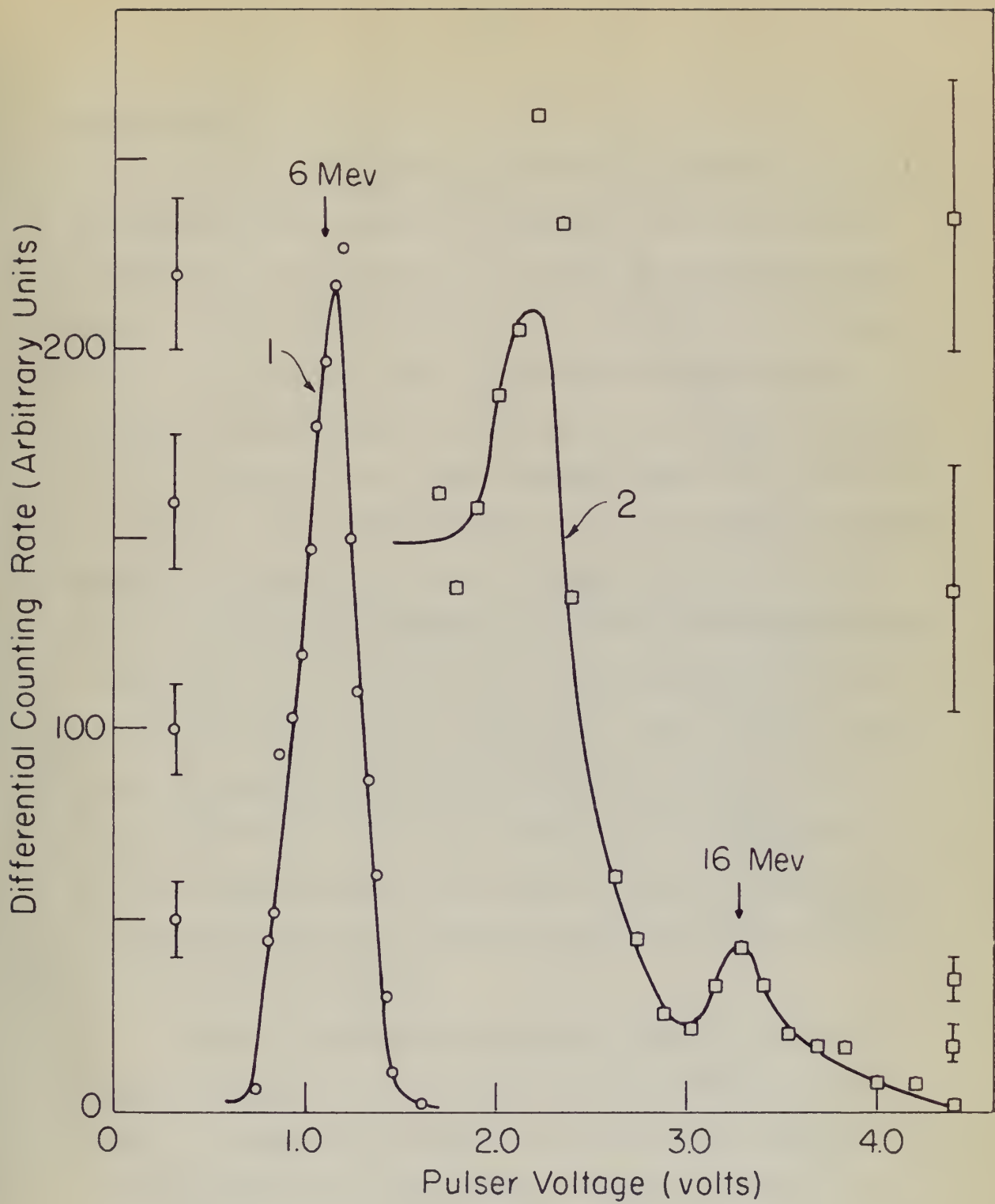
### Figure 13

#### Energy Calibration

Curve No. 1 was obtained by proton bombardment of a thick CaF target; curve No. 2 by proton bombardment of a thick  $B_4C$  target. A 16-mil lead converter was used for both curves. The boron curve (No. 2) from 1.5 - 2.5 volts was obtained with poor statistics and normalized to match the 2.5 - 4.5 volt section. There is some evidence of the 12-Mev line at 2.3 volts. The anticoincidence circuit had not been designed when these runs were made.









## FLUORINE RUMS

The low-energy limitation of the spectrometer is imposed by the rapid decrease of the pair production cross section with decreasing energy, combined with the increase in Compton cross section. At about 5 Mev (where these two cross sections are about equal), the resolution of the spectrometer is limited by the inability of discriminator No. 2 to perform its designed function; that is, separation of the doubly ionizing pulses of the pair process from the singly ionizing pulses of the Compton recoil electrons. Figure 14 illustrates the lack of a definite separation between pairs and Compton recoil electrons for 6-Mev incident x-ray energy. A sufficiently thin converter with a very thin scintillator No. 2 would perform this function at, say, 3 Mev, since multiple scattering in the converter and in the scintillator, with consequent increased fluctuations in the energy loss, would be minimized. A point is reached, however, where light collection difficulties and photomultiplier statistics impose a lower energy limit to the usefulness of the spectrometer.

Figure 15 illustrates the effect of changes in spectrum shape with changes in D1. In order for the spectrometer to function, it is necessary that there be a region where changing D1 does not materially affect spectrum shape. Figure 15 illustrates that such a plateau does in fact exist; that is, changing D1 from very

# DISCUSSION

The low-energy limit of the spectrometer is imposed by

the rapid decrease of the pair production cross section with de-  
creasing energy, combined with the increase in Compton cross sec-  
tion. At about 5 keV (where these two cross sections are about

equal), the resolution of the spectrometer is limited by the  
stability of discriminator No. 2 to perform the desired function;  
that is, separation of the doubly ionizing peaks of the pair pro-  
cess from the singly ionizing peaks of the Compton recoil electrons.

Figure 11 illustrates the lack of a definite separation between  
pair and Compton recoil electrons for 6-MeV incident x-ray energy.

A sufficiently thin converter with a very thin collimator No. 2  
would perform this function at 5, 3, 1 MeV, since multiple scatter-  
ing in the converter and in the collimator, with consequent in-  
creased fluctuations in the energy loss, would be minimized. A

point is noted, however, where light collection difficulties and  
photoelectron statistics impose a lower energy limit to the use-

fulness of the spectrometer.

Figure 12 illustrates the effect of changes in spectrum  
shape with changes in E<sub>1</sub>. In order for the spectrometer to func-  
tion, it is necessary that there be a region where changing E<sub>1</sub> does  
not materially affect spectrum shape. Figure 12 illustrates that  
such a plateau does in fact exist; that is, changing E<sub>1</sub> from very

Figure 14

Pulse-Height Distribution for Scintillator No. 2 at 6 Mev

This curve was obtained by the proton bombardment of a thick CaF target using a 16-mil lead converter. The standard statistical errors of the points are indicated to the right of the curve.





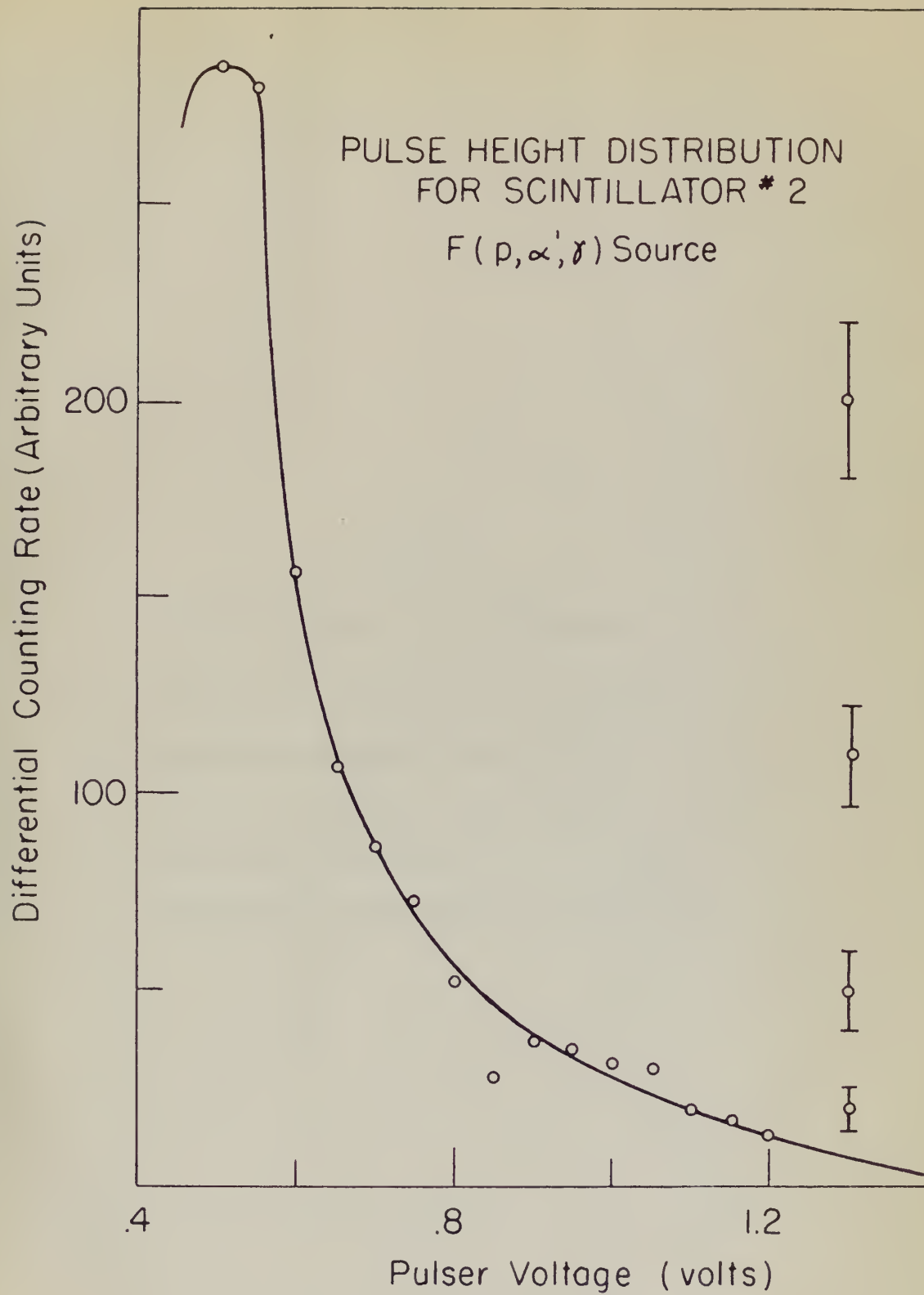




Figure 15

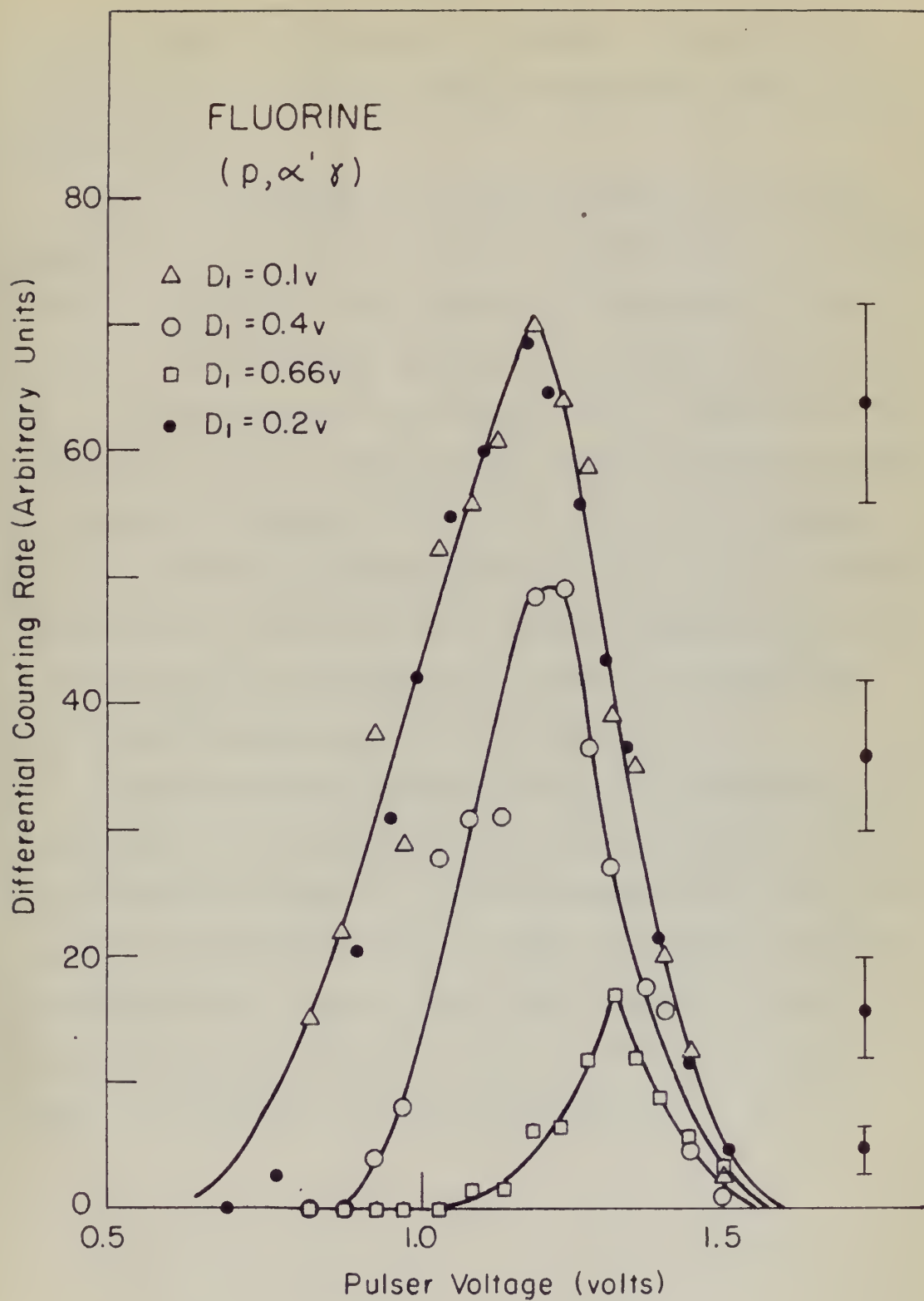
Effect of Changing Discriminator No. 1

All curves in this figure were obtained by proton bombardment of a thick CaF target using a 16-mil lead converter. These curves are normalized to the same number of protons incident on the target.

Figure 12

Effect of changing dimensions No. 1  
All curves in this figure were obtained  
in various positions of a disk 50  
degrees with a 10-11 inch diameter.  
These curves are normalized to the same  
number of points incident on the target.







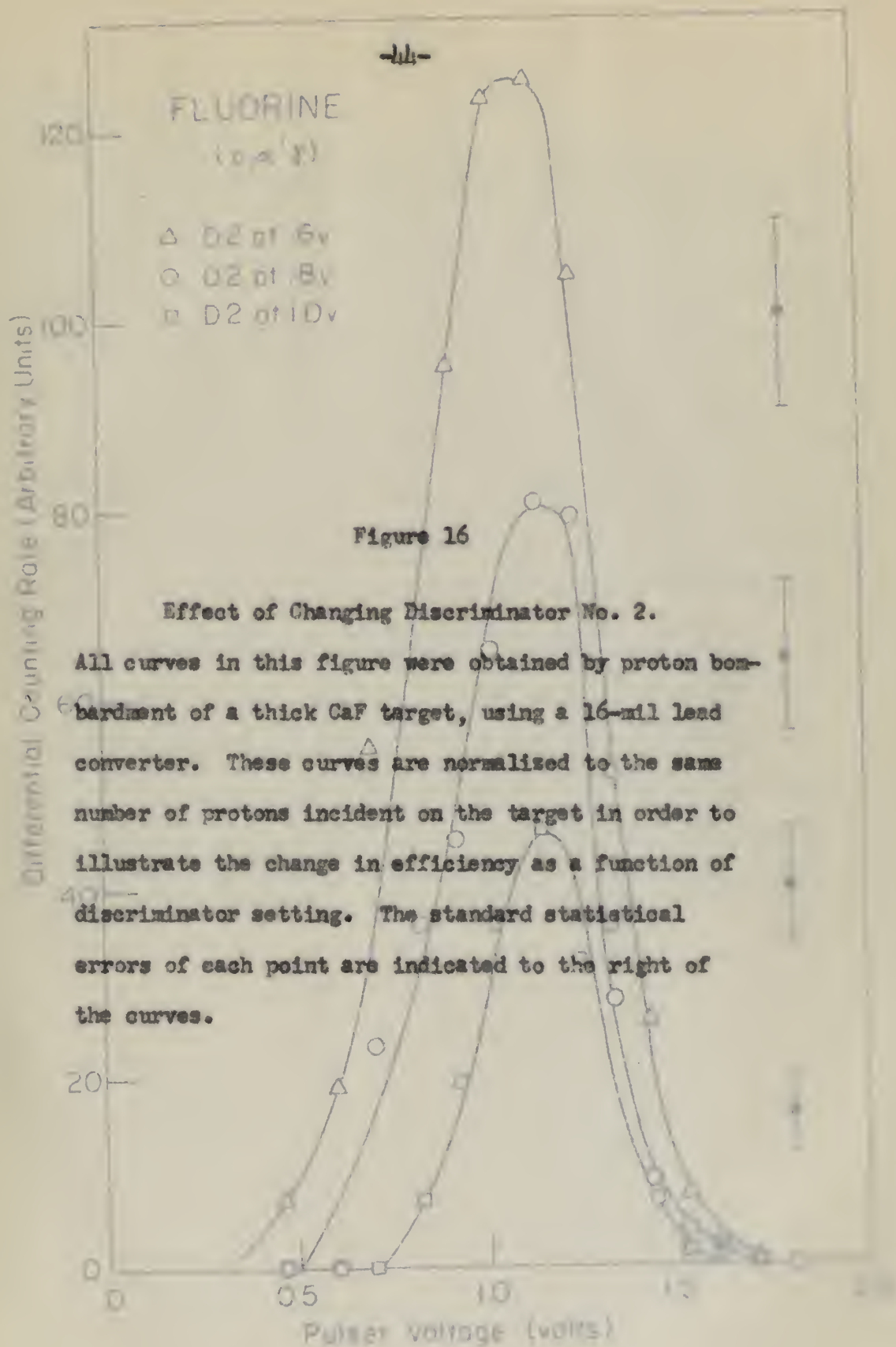
low to 0.2 volts does not affect the position of the peak or the resolution. D1 at 0.2 volts requires at least 1-Mev energy loss in scintillator No. 1.

Figure 16 illustrates the change in efficiency of the spectrometer with changes in the setting of discriminator No. 2 at 6-Mev incident x-ray energy. These curves were all made with the same setting of D1; that is, 0.2 volts, and normalized to the same number of protons incident on the  $F^{19}(p, \alpha' \gamma)$  target. Hence, the ratio of the areas under the curves of Figure 16 gives directly the ratio of spectrometer efficiency for the given discriminator settings. These ratios are 1:2:3.8, in agreement with the shape of the distribution curve for scintillator No. 2 shown in Figure 11. The curve for D2 = 0.8 volts corresponds to an efficiency of  $8 \times 10^{-3}$  for 6-Mev incident x-ray energy, 16-mil lead converter.

Considering the contribution of the 7-Mev fluorine line, the resolution at 6 Mev is about 25 percent, which is about the resolution predicted in Chapter V. The lowest energy at which the present spectrometer is useful is 6 Mev. To reduce this limit, to improve the resolution at 6 Mev, and perhaps more important to obtain a better plateau of efficiency as a function of D2 would require a thinner lead converter and a thinner scintillator No. 2.

low to 0.2 volts does not affect the position of the peak or the resolution. If at 0.2 volts requires at least 1-mev energy loss in scintillator No. 1.

Figure 10 illustrates the change in efficiency of the spectrometer with changes in the setting of discriminator No. 2 at 6-mev incident x-ray energy. These curves were all made with the same setting of DI, that is, 0.2 volts, and normalized to the same number of photons incident on the  $^{137}\text{Cs}$  source. Hence, the ratio of the areas under the curves of Figure 10 gives directly the ratio of spectrometer efficiency for the given discriminator settings. These ratios are 1:1.3:1.8, in agreement with the slope of the distribution curve for scintillator No. 2 shown in Figure 11. The curve for DI = 0.2 volts corresponds to an efficiency of  $8 \times 10^{-3}$  for 6-mev incident x-ray energy, 10-mev lead converter. Considering the contribution of the 7-mev line, the resolution at 6 mev is about 25 percent, which is about the resolution predicted in Chapter V. The lowest energy at which the spectrometer is useful is 6 mev. To reduce this limit, to improve the resolution at 6 mev, and thereby more important to obtain a better picture of efficiency as a function of E would require a thinner lead converter and a thinner scintillator No. 2.





low to 0.2 volts does not affect the position of the peak or the resolution. DI at 0.2 volts requires at least 1-mev energy loss in scintillator No. 1.

Figure 10 illustrates the change in efficiency of the spectrometer with changes in the setting of discriminator No. 1 at 0-mev incident x-ray energy. These curves were all made with the same setting of DI that is, 0.2 volts, and normalized to the same number of pulses incident on the  $^{10}\text{P}_4(\gamma)$  source. Hence, the ratio of the areas under the curves of Figure 10 gives directly the ratio of spectrometer efficiency for the given discriminator settings. These ratios are 1:0.33, in agreement with the ratio of the discriminator curves for scintillator No. 2 shown in Figure 11. The curve for DI = 0.2 volts corresponds to an efficiency of  $3 \times 10^{-3}$  for 0-mev incident x-ray energy, 10-mil lead converter.

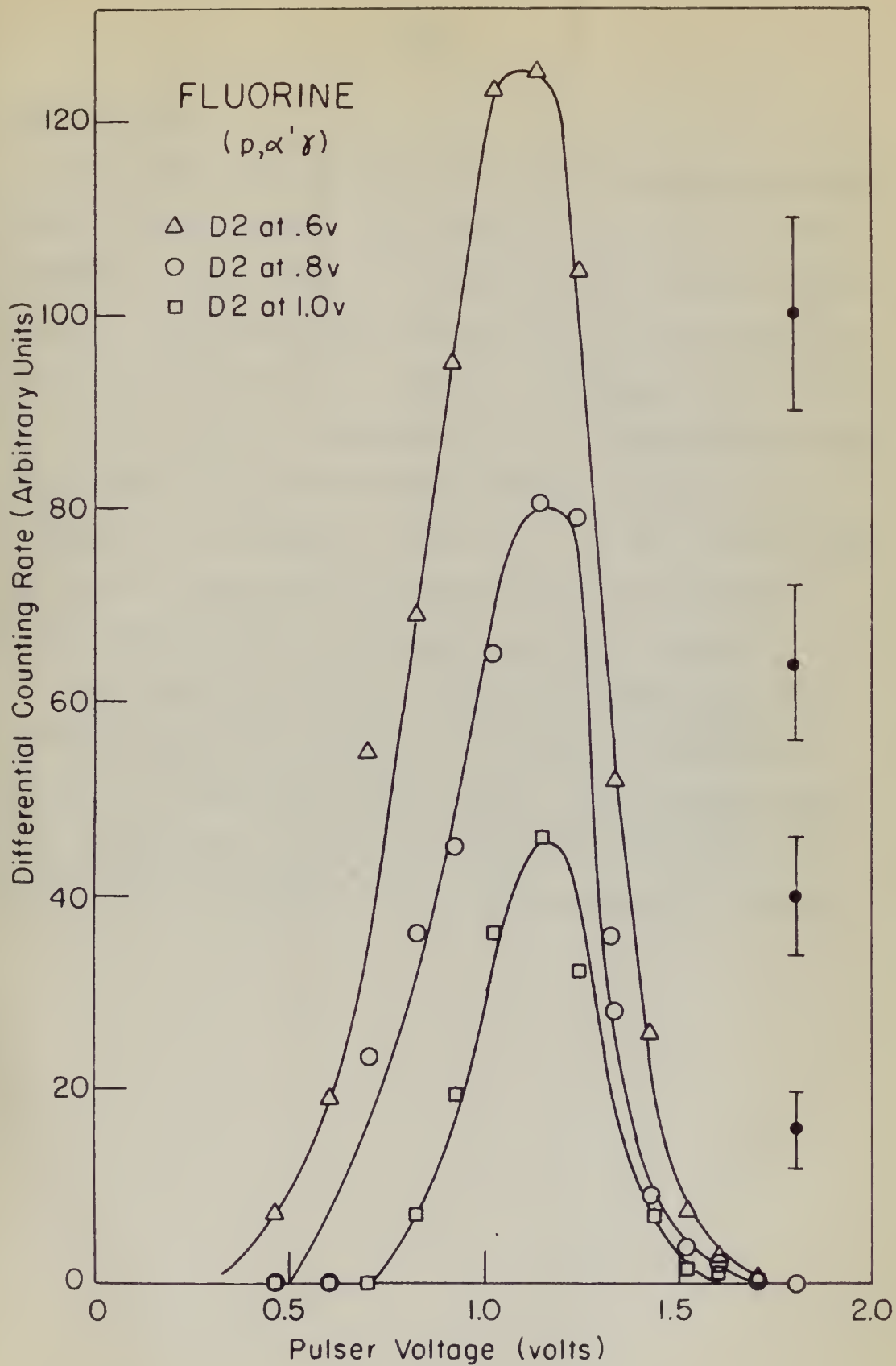
Considering the contribution of the 7-mev fission line, the resolution at 0 mev is about 97 percent, which is about the resolution predicted in Chapter V. The lowest energy at which the present spectrometer is useful is 0 mev. To reduce this limit, to improve the resolution at 0 mev, and perhaps more important to obtain a better picture of efficiency as a function of energy would require a thinner lead converter and a thinner scintillator No. 2.

Figure 16

Effect of Changing Discriminator No. 2.

All curves in this figure were obtained by proton bombardment of a thick CaF target, using a 16-mil lead converter. These curves are normalized to the same number of protons incident on the target in order to illustrate the change in efficiency as a function of discriminator setting. The standard statistical errors of each point are indicated to the right of the curves.

errors of each point are indicated in the right of  
 distribution existing. The standard conventional  
 illustrates the change in efficiency as a function of  
 number of points indicated on the graph in order to  
 computer. These points are normalized to the same  
 pattern of a thick line segment, which is 10-mil long  
 All curves in this figure were obtained by vector sum-







## HIGH-ENERGY RUNS

The difficulties apparent in the high-energy region, as illustrated by Figure 13, led to the necessity for design of the anticoincidence circuit. Figure 17 illustrates the difficulty in distinguishing singly and doubly ionizing events with the anticoincidence scintillator out of the circuit. This figure also demonstrates the apparent success of scintillator No. 3 in eliminating high background effects which mask the expected doubly ionizing peak calculated and shown on Figure 9 of Chapter III. To date, the only runs made with the anticoincidence unit in operation were the pulse-height distribution in scintillator No. 2 shown in Figure 17.

The prediction in Chapter V regarding electron escape and radiation loss from scintillator No. 1 should be experimentally verified by a high-energy electron source. The high-energy limit of the spectrometer is imposed as a result of rapidly increasing electron escape probability with increasing energy above 15 Mev.

HIGH-ENERGY RAYS

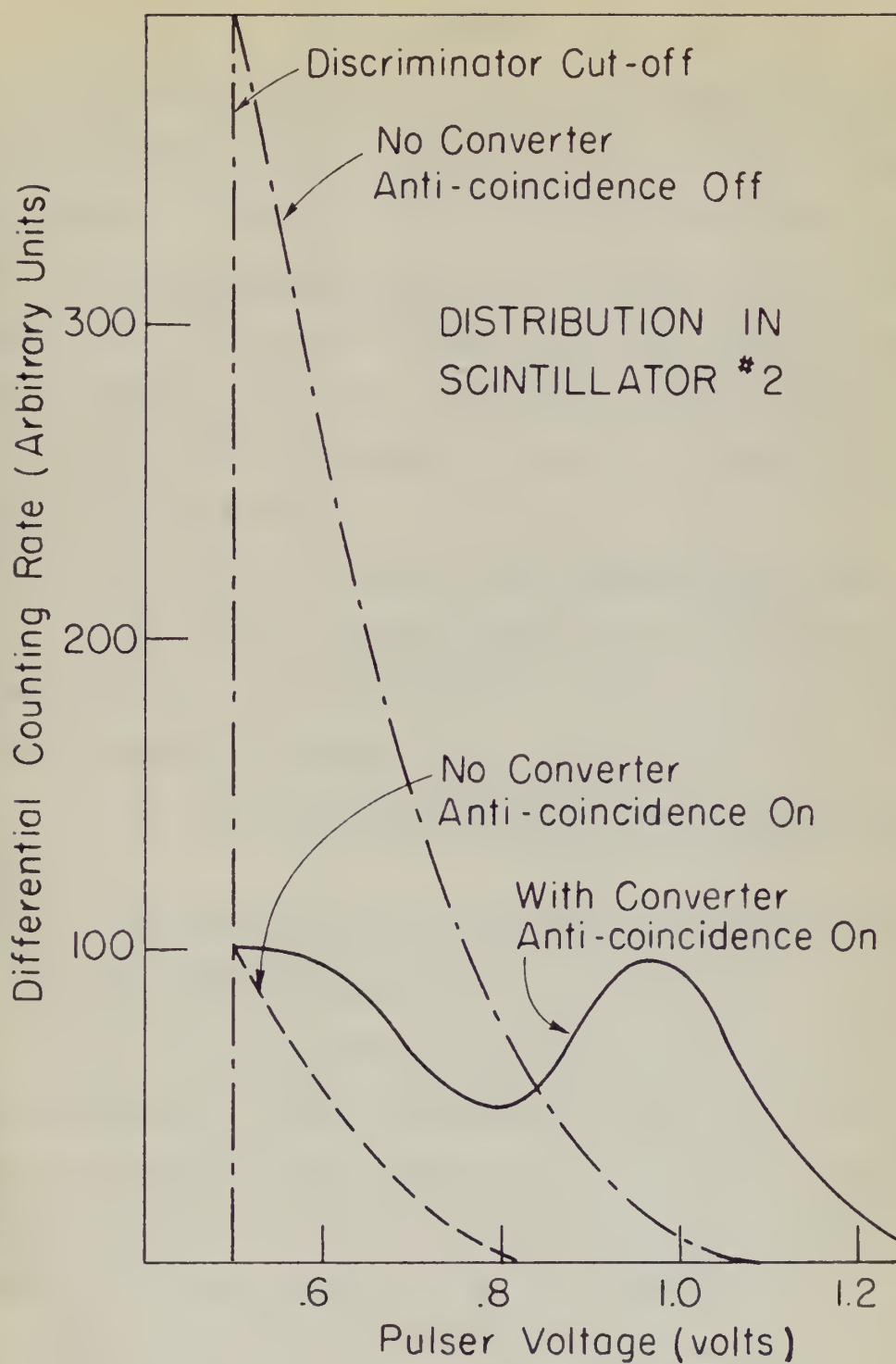
The distribution spectrum in the high-energy region, as illustrated by Figure 11, led to the necessity for design of the end-collectors circuit. Figure 12 illustrates the difficulty in this region due to the high-energy region and the high-energy region. The figure also demonstrates the apparent necessity of collector No. 2 in eliminating high back-ground counts which may be caused by the high-energy region. It is noted and shown on Figure 2 of Chapter III. In fact, the only way to deal with the end-collectors unit in operation were the following distribution in collector No. 2 shown in Figure 13.

The position in Chapter V regarding electron escape and radiation loss from collector No. 1 should be experimentally verified by a high-energy electron source. The high-energy limit of the spectrum is known as a result of rapidly increasing electron escape probability with increasing energy above 15 Mev.

Figure 17

Effect of the Anticoincidence Circuit at 17 Mev  
The curves shown were obtained by proton bombardment of a thick lithium metal target, using a 16-mil lead converter. The need for the anticoincidence circuit at high x-ray energy is illustrated.









### VIII. SUMMARY

An attempt has been made to design, instrument, and calibrate an x-ray scintillation pair spectrometer capable of 10 percent resolution at 10 Mev. The spectrometer is designed for use at the M. I. T. linear accelerator and consequently must span the 5- to 17-Mev x-ray energy region. This three scintillator telescope arrangement relies on the ability of a thin plastic scintillator to distinguish the doubly ionizing pulses originating in the thin lead converter as a result of the pair process.

Careful study of the 6-Mev fluorine gamma-ray has shown:

1. That the observed resolution of 20 to 25 percent is in agreement with predicted values for the thickness of the lead converter and plastic scintillator used;
2. That coincidence pulses are doubly ionizing events, and;
3. Better resolution can be obtained by using a thinner lead converter and thinner plastic scintillator No. 2.

Study of the high-energy incident x-ray region, using the 17-Mev lithium gamma-ray, demonstrated that an anticoincidence circuit was necessary to distinguish doubly ionizing events. Subsequent experimental observations of the pulse height distribution in scintillator No. 2 pointed to the apparent success of the anticoincidence circuit. A program similar to that performed at 6 Mev remains to be carried out at 17 Mev to determine optimum operating conditions in this energy region.

# VIII. DISCUSSION

An attempt has been made to design, construct, and calibrate an x-ray scintillation beta spectrometer capable of 10 percent resolution at 10 Mev. The spectrometer is designed for use at the N. I. T. linear accelerator and consequently must span the 2- to 17-Mev x-ray energy region. This poses scintillator selection requirements relative to the ability of a thin plastic scintillator to distinguish the heavily ionizing pulses originating in the thin lead converter as a result of the beta process.

Careful study of the 6-Mev Thulium gamma-ray has shown:

1. That the observed resolution of 20 to 22 percent is in agreement with predicted values for the thickness of the lead converter and plastic scintillator used;
2. That coincidences exist for heavily ionizing events;

and;

3. Better resolution can be obtained by using a thinner lead converter and thinner plastic scintillator No. 1.
- Study of the high-energy incident x-ray region, using the 17-Mev Thulium gamma-ray, demonstrated that an anticoincidence circuit was necessary to distinguish heavily ionizing events. Subsequent experimental observations of the pulse height distribution in scintillator No. 2 pointed to the apparent success of the anticoincidence circuit. A program similar to that performed at 6 Mev remains to be carried out at 17 Mev to determine whether operating conditions in this energy region

# APPENDIX I

## CALCULATION OF DIFFERENTIAL ENERGY LOSS DISTRIBUTION FOR SCINTILLATOR No. 2 AT 17.6-Mev INCIDENT X-RAY ENERGY

Using the electron energy distributions given by Johns et al.<sup>24</sup> in tabulated form for 1-Mev energy intervals (17.6-Mev incident x-ray energy) and the angular distribution in terms of the electron energy, it is possible to calculate a theoretical energy loss distribution curve for scintillator No. 2 in the following manner. The angle a Compton recoil electron makes with the incident photon is fixed for a given photon energy by the relation<sup>25</sup>

$$\tan^2 \theta/2 = \frac{2\alpha(\gamma/E - 1) - 1}{(1 + \alpha)^2}$$

where  $\gamma$  = energy of incident photon in Mev;

$E$  = energy of recoil electron;

$\alpha = \gamma/mc^2$ ;

$mc^2$  = electron rest mass, 0.51 Mev.

The average angle between the direction of motion of a created electron (positive or negative) and of the photon is<sup>9</sup>

$$\theta_0 = \frac{mc^2}{E}$$

where  $E$  is the energy of the electron.



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Once the electron enters the scintillator, it no longer travels in its initial direction given by  $\phi_E$  or  $\theta_0$ , but is subjected to single and multiple scattering. One method of finding the actual path length of electrons has been discussed by Yang<sup>26</sup>. Yang uses a correction  $\Delta$  such that  $t' = t + \Delta$ , where  $t'$  is the actual path length and  $t$  is the foil thickness measured in radiation lengths<sup>27</sup>.

$$\Delta_{\text{average}} = \frac{t^2 E_s^2}{4P^2 \beta^2},$$

where  $E_s$  = characteristic energy = 21.2 Mev;

$P$  = electron momentum in Mev;

$\beta$  = velocity of electron in units of the velocity of light.

This result was derived from the gaussian approximation of Rossi<sup>27</sup> but could be obtained from the exact numerical solution of Snyder and Scott<sup>28</sup>. It is felt that the gaussian approximation is of reasonable accuracy for these calculations and will be used throughout this paper when investigating multiple scattering effects. Using the above formula and the collision loss as a function of energy given in Johns et al<sup>24</sup>, it was possible to prepare the histogram shown in Figure 9 for the 17.6-Mev lithium gamma-ray.

The Compton cross section at 17.6 Mev was obtained from Davisson and Evans<sup>25</sup>; but, since the observed pair production cross sections

Since the electron velocity is infinitesimal, it is no longer  
 treated in the initial distribution given by  $\delta^3 \mathbf{v}$ , but is now  
 treated as a single and definite quantity. The method of finding  
 the actual path length of electrons has been discussed by Lang<sup>24</sup>.  
 That with a correction  $\delta$  such that  $\delta' = \delta + \lambda$ , where  $\delta'$  is the  
 actual path length and  $\delta$  is the full thickness measured in vacuo.  
 then follows<sup>25</sup>.

$$A_{\text{average}} = \frac{\int_0^\delta A e^{-\mu x} dx}{\int_0^\delta e^{-\mu x} dx}$$

where  $\mu$  = absorption coefficient =  $21.5 \text{ cm}^{-1}$   
 $\lambda$  = electron mean free path  
 $\delta$  = velocity of electron in units of the velocity of light.

This result was derived from the expansion approximation of  
 Lang<sup>27</sup> but could be obtained from the exact numerical solution of  
 Lang<sup>28</sup> and Lang<sup>29</sup>. It is this that the expansion approximation is

of reasonable accuracy for these calculations and will be used  
 throughout this paper when investigating multiple scattering ef-  
 fects. Using the above formula and the collision loss as a func-  
 tion of energy given in Table 2, it was possible to improve  
 the histogram shown in Figure 2 for the 17.6-MeV electron beam.  
 The two curves shown in Figure 2 are obtained from Lang<sup>27</sup>  
 and Lang<sup>29</sup>, but since the observed self production cross section

for lead above 5 Mev differ as much as 10 percent from the calculated values, the value for the pair cross section was the experimental value obtained by Waller<sup>29</sup>.

The energy loss of the electrons in the converter has not been taken into account in any of the curves shown in Figure 9. Hough<sup>30</sup> gives the probability of emission at an angle greater than  $\theta_1$  (for large angles) as roughly:

$$\frac{3}{8} \left( \frac{mc^2}{E} \right)^2 \frac{1}{1 - \cos \theta_1}$$

where  $E$  is the energy of the observed electron. From this, it can be seen that the actual pair angular distribution will spread the energy loss in scintillator No. 2 out towards the higher energy (longer actual path length). The finite resolution of the photomultiplier will spread the distribution out on both sides of the peak. The resulting qualitative curve is shown in Figure 9.



The fact that the difference is as small as 10 percent from the calculated

values, the value for the error margin was the experimental

error obtained by Gellert.

The energy loss of the electrons in the experiment has not been

taken into account in any of the curves shown in Figure 2. (Gellert)

From the probability of selection at an angle greater than  $\theta_1$  for

large angles, we conclude

$$\frac{1}{1 - \cos \theta_1} \left( \frac{1}{2} \left( \frac{1}{1 - \cos \theta_1} \right) \right)$$

where  $\theta_1$  is the energy of the scattered electron. From this, it can

be seen that the actual value of the probability will exceed the

energy loss in scattering. It was assumed the higher energy

(lower energy) was larger. The value of the probability of the

electron will exceed the theoretical one on both sides of the

peak. The resulting calculation curve is shown in Figure 3.

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BIBLIOGRAPHY

1. H. W. Koch and R. S. Foote, *Phys. Rev.* 91, 455 (1953).
2. J. L. Burkhardt, Ph.D. Thesis, M.I.T., February 1955.
3. H. W. Koch and R. S. Foote, *Rev. Sci. Inst.* 25, 746 (1954).
4. R. L. Walker and B. D. McDaniel, *Phys. Rev.* 74, 315 (1948).
5. B. B. Kinsey and G. A. Bartholomew, *Can. J. Phys.* 31, 537 (1953).
6. R. R. Carlson et al, *Phys. Rev.* 94, 1311 (1954).
7. J. K. Bair and F. C. Maieschein, *Rev. Sci. Inst.* 22, 343 (1951).
8. S. A. E. Johansson, *Nature* 166, 794 (1950); *Phil. Mag.* (London) 43, 249 (1952).
9. Segre, Experimental Nuclear Physics, Vol. I (1953), John Wiley and Sons (New York).
10. R. K. Swank, *Annual Review Nuclear Science* 4, 111 (1954).
11. T. Huus and R. B. Day, *Phys. Rev.* 91, 599 (1953).
12. R. L. Walker, *Phys. Rev.* 79, 172 (1950).
13. H. Mark and G. Goldring, Rockefeller Generator Group, M.I.T., private communication.
14. J. G. Campbell and A. J. F. Boyle, *Australian J. Phys.* 6, 171 (1953).
15. W. Heitler, The Quantum Theory of Radiation, Clarendon Press, Oxford (1936).
16. W. A. Fowler and C. C. Lauritsen, *Phys. Rev.* 76, 314 (1949).
17. C. N. Chou, *Phys. Rev.* 87, 376 (1952).



REFERENCES

1. W. R. Rook and R. R. Taylor, *Proc. Roy. Soc. (1953)*.
2. M. L. Huggins, *Phil. Mag.*, **1**, 1, 1 (1953).
3. W. R. Rook and R. R. Taylor, *Proc. Roy. Soc. (1954)*.
4. W. R. Rook and R. R. Taylor, *Proc. Roy. Soc. (1955)*.
5. W. R. Rook and R. R. Taylor, *Proc. Roy. Soc. (1956)*.
6. W. R. Rook and R. R. Taylor, *Proc. Roy. Soc. (1957)*.
7. J. E. Hall and R. R. Taylor, *Proc. Roy. Soc. (1958)*.
8. J. E. Hall and R. R. Taylor, *Proc. Roy. Soc. (1959)*.
9. *Proc. Roy. Soc. (1960)*.
10. W. R. Rook, *Proc. Roy. Soc. (1961)*.
11. W. R. Rook and R. R. Taylor, *Proc. Roy. Soc. (1962)*.
12. W. R. Rook, *Proc. Roy. Soc. (1963)*.
13. W. R. Rook and R. R. Taylor, *Proc. Roy. Soc. (1964)*.
14. W. R. Rook and R. R. Taylor, *Proc. Roy. Soc. (1965)*.
15. W. R. Rook, *Proc. Roy. Soc. (1966)*.
16. W. R. Rook and R. R. Taylor, *Proc. Roy. Soc. (1967)*.
17. W. R. Rook, *Proc. Roy. Soc. (1968)*.

18. L. Katz and A. S. Penfold, *Revs. Modern Phys.* 24, 28 (1952).
19. Pilot Chemical Company, Waltham, Massachusetts.
20. S. Janes, Synchrotron Laboratory, M. I. T., private communication.
21. K. H. Spring, Photons and Electrons, John Wiley and Sons, New York (1950).
22. R. D. Evans, The Atomic Nucleus, McGraw-Hill, to be published.
23. R. M. Sternheimer, *Phys. Rev.* 88, 851 (1952).
24. H. E. Johns et al, *Nucleonics*, 12, 40 (1954).
25. C. M. Davisson and R. D. Evans, *Revs. Modern Phys.* 24, 79 (1952).
26. C. N. Yang, *Phys. Rev.* 84, 599 (1951).
27. B. Rossi and K. Greisen, *Revs. Modern Phys.* 13, 240 (1941).
28. H. Snyder and W. T. Scott, *Phys. Rev.* 76, 220 (1949).
29. R. L. Walker, *Phys. Rev.* 76, 527 (1949).
30. P. V. C. Hough, *Phys. Rev.* 74, 80 (1949).
31. R. K. Swank and W. L. Buck, *Nucleonics* 10-5, 51 (1952).
32. B. R. Linden, *Nucleonics* 11-9, 30 (1953).
33. J. Saldick and A. O. Allen, *J. Chem. Phys.* 22, 438 (1954).
34. H. A. Bethe and W. Heitler, *Proc. Roy. Soc. (London)*, A46, 83 (1934).
35. L. Eyges, *Phys. Rev.* 77, 81 (1950).
36. E. S. Rosenblum, AECU Report No. 1825 (1951).
37. W. Paul and H. Reich, *Z. Physik* 127, 429 (1950).
38. J. J. S. Chen and S. D. Warshaw, *Phys. Rev.* 84, 355 (1951).
39. Goldwasser et al, *Phys. Rev.* 88, 1137 (1952).

18. L. B. and A. D. Boudin, Paris, France 1925, 25 (1925).
19. J. B. Boudin, Paris, France 1925, 25 (1925).
20. L. B. Boudin, Paris, France 1925, 25 (1925).
21. L. B. Boudin, Paris, France 1925, 25 (1925).
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37. L. B. Boudin, Paris, France 1925, 25 (1925).
38. L. B. Boudin, Paris, France 1925, 25 (1925).
39. L. B. Boudin, Paris, France 1925, 25 (1925).

40. L. Landau, J. Phys. USSR) 8, 201 (1944).

41. Fano, Nucleonics, 11-8, 8 (1953).



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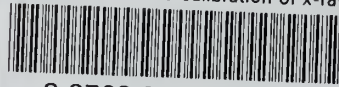
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